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INSTRUCTIONS

FOR

TESTING TELEGRAPH LINES.

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INSTRUCTIONS

FOR

TESTING TELEGRAPH LINES

AND THE

TECHNICAL ARRANGEMENTS OF OFFICES.

ORIGINALLY WRITTEN ON BEHALF OF THE GOVERNMENT OF INDIA,
UNDER THE ORDERS OF THE DIRECTOR-GENERAL
OF TELEGRAPHS IN INDIA,

BY

LOUIS SCHWENDLER.

VOL. I.

Second Edition,

AUTHORISED BY H.M. SECRETARY OF STATE FOR INDIA IN COUNCIL.

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INTRODUCTION.

The Testing-Instructions were originally written for the special use of the Staff of the Government Telegraph Department in India, to facilitate the introduction of a rational system of Testing the Lines and the technical arrangement of Telegraph Offices.

The *first* Instructions were issued to the Department in 1869. They formed a small book, containing about 48 pages only, and were prepared in a hurry under the pressure of other work, and during almost incessant travelling. Completeness could therefore not be expected, but the book was nevertheless well received *within* and *without* the Department. Many of the results given were soon quoted in professional text-books, and other Administrations asked the Government for copies of the book. I thus felt encouraged to elaborate the system of Testing further, and being in this endeavour liberally supported by Government, and friendly guided by the late Major-General D. G. Robinson, R.E., the Director-General of Telegraphs in India, I succeeded in writing a number of books (between 1869 and 1876), printed by Government, which contained, in addition to my own researches, not published anywhere else, all that which practice had shown to be necessary in order to get a real practical value out of a system of Testing, which, up to the time, no other Telegraphic Administration had established on so large and liberal a scale.

The last part of this work appeared in 1876, shortly after I had left India for Europe on furlough. Here I found that the Testing instructions, although prepared for a special purpose, and under the influence of local circumstances, had already obtained recognition amongst the profession. I therefore readily gave way to the pressure of friends and others interested in the subject to publish a second revised edition in London. To this Her Majesty's Secretary of State for India in Council gave his sanction, and the first volume is herewith issued; the second volume will not be published before my arrival in India, since it is thought desirable to embody in it all those alterations and improvements which have been made during my absence.

Every one acquainted with the introduction of a system of observations, distributed over an enormous area and conducted by hundreds of officers, will readily understand the many difficulties to be contended with before coming to any practical issue. I am happy to be able to state, however, that success was more rapidly obtained than I had anticipated. This has been chiefly due to the very great interest taken in the subject by all those officers of the Department whom the Director-General had especially deputed for the work.

However much Testing may become routine by continual practice, it *will* always, and *should* always, partake of something of the nature of a physical experiment, which must be conducted with a perfectly clear understanding. Then only can the Tester draw the right conclusions from his observed facts; then only can Testing become of real benefit to the Administration.

In India these conditions have been fulfilled. There is a large staff of officers available, with a first-rate general education, with a strong desire for improvement; and many of them are well trained in conducting physical experiments. To all these officers my thanks are due. Further, the great assistance rendered me by Mr. R. S. Brough, Assistant Superintendent, Government Telegraphs in India, in bringing out the first edition, I am also most desirous to acknowledge here especially.

I found that one of the greatest difficulties is the proper recording of results, the compilation and computation of Tests (in fact, all that which might be termed the clerical part of the system), in order to draw the final conclusions, and to be able to prepare the orders thereon.

In several Appendices I have given the full description of the system as it at present stands in India. There is still much improvement possible.

During my stay in Europe I have had many opportunities to watch the working of other Telegraph Administrations, and have been surprised to find how little progress Testing has made. I was always told: "Yes, we should like to introduce a general system of Testing; we know its great practical utility; but show us a system to do it, and which will work satisfactorily."

Here is a book which I believe contains such a system; and although I am well aware of its many defects, I know it has done good service in India, and by it the objects in view have been obtained, *i.e.*:—We know quantitatively the electrical state of the lines at all hours of the day, and seasons of the year; we are able to localise faults of all kinds very accurately, and repair them with despatch; we test all our telegraphic material, and by it have greatly improved its essential qualities; we are not groping in the dark any more—we *measure* and *know*.

Other Telegraph Administrations will find the book equally useful, although the circumstances may be slightly different.

LOUIS SCHWENDLER.

LONDON, 1*st October* 1878.

INSTRUCTIONS FOR TESTING TELEGRAPH LINES.

PART I.

ON LINE-TESTING ARRANGEMENTS.

Arrangements for the testing of Lines, based on the "differential" method, have proved the most successful and convenient in practice. Of these, that form known as "Wheatstone's Electrical Balance" or "Wheatstone's Bridge" is by far the best—it combines simplicity of arrangement with great accuracy and sufficient sensibility through wide ranges.

Kirchoff was the first to call the attention of physicists to this most beautiful method of comparing accurately electrical resistances; but, although subsequently it was made use of in scientific researches in Germany, it was not employed for telegraphic purposes until embodied by Sir Charles Wheatstone and Dr. Werner Siemens in a more practical and convenient form.

Next to the Bridge, the "Differential Galvanometer," having two coils with equal magnetic moments, may be said to follow; but, for the same bulk and cost, it can never combine the same accuracy and sensibility within wide limits as the Bridge.

However, both arrangements being in use, a full description and mathematical theory of each will be given in the following two Sections.

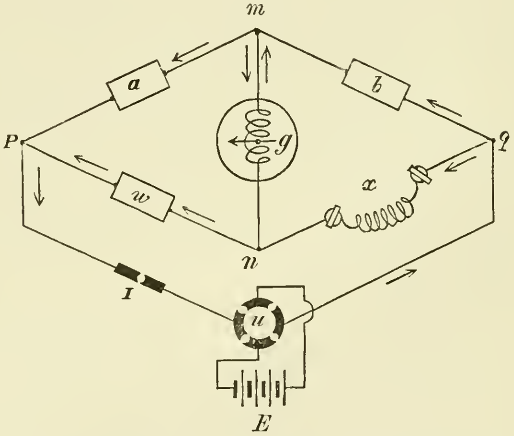
SECTION I.

WHEATSTONE'S BRIDGE.

I. *Explanation of the Diagram.*—Figure 1 gives a diagram of a Wheatstone's Bridge.

a and b are the "branch resistances," which in practice, as a general rule, contain each three coils having resistances of 10, 100, and 1000 units respectively.

Fig. 1.



w is the "comparison coil," the resistance of which can be varied between 1 and 10,000 units.

x is the unknown resistance to be measured, expressed in terms of the same units as w.

g is a sensitive galvanometer, having a resistance of g units.

E is the electromotive force of the testing battery.

u is a battery reverser. .

Plug 1 closes the battery circuit.

II. *Explanation of the System.*—The circuit having been completed by inserting the plug 1, it may be said that the current enters the Bridge at the point q, and leaves it at the point p. The galvanometer consequently receives two currents,[1] opposite in direction, which tend to neutralise each other in their action on the needle, and which, if of unequal strength, will cause a deflection, either to the right or to the left. Should, however, these currents be of equal strength, *the needle will remain at rest.* The equalisation of these two currents is the main principle of testing with Wheatstone's Bridge, and it is effected by altering w, the resistance of the comparison coil. When balance of the currents in the galvanometer is established, the following relation exists between the four resistances, a, b, w, and x:

$$a\,x = b\,w$$

whence

$$x = \frac{b}{a}\,w \qquad \ldots \qquad \ldots \qquad \ldots \qquad (1)$$

and by this formula x can always be calculated, since a and b are two known quantities, and w is found by experiment.

If $a = b$, then the formula becomes

$$x = w$$

that is, in this case the unknown resistance is identical with the observed resistance w.

It can be easily shown by general reasoning, without going into the mathematical question, that there exists *some* value of w, for any given value of x and a fixed ratio $\frac{b}{a}$, for which the needle will be brought to zero. For, suppose we make $w = o$; then, of the current entering at q, all that which arrives at n will pass on through w to p, but of that which arrives at m a part will flow through g and w to p. Hence there will be a deflection of the needle produced—to the right hand say. Again, suppose we make $w = \infty$; then, of the current entering at q, all that which arrives at m will pass on through a to p, and all that which arrives at n will pass through g and a to p. Hence there will be a deflection of the needle produced, and in a direction opposite to that of the first deflection, *i.e.*, to the left hand.

---

[1] Of course actually there is always only *one* current of given strength and sign in the galvanometer, never *two.* But, as in our mind, although it may not be the case in nature, any such given current can be considered as a difference of *two* currents, I have kept to this explanation, because it appears to me that it illustrates the principle, especially to beginners, clearer than any other one.

Thus, since for $w = o$ the needle is deflected in one direction, and for $w = \infty$ the needle is deflected in the opposite direction, and that the needle, in passing from the one direction to the other, must pass through zero, there must be some value of w between o and ∞ for which the needle will be deflected in neither direction.[1]

The above can be at once proved by Ohm's Law.[2]

For let V be the potential at p
" V' " " q
" U " " m
" U' " " n

Then, when balance is established, U' must be equal to U; and, therefore, the current from p to q through a and b must be uniform, that is

$$\frac{V - V'}{a + b} = \frac{U - V'}{b} \qquad \dots \qquad \dots \qquad (a.)$$

---

[1] This shows that there is some value, but does not show that there is only *one* value.

[2] *Vide* Appendix I.

and, similarly, the current from p to q, through w and x, must be uniform, that is (remembering that $U' = U$)

$$\frac{V - V'}{w + x} = \frac{U - V'}{x} \qquad \ldots \qquad \ldots \qquad (b.)$$

and combining (a) and (b)

$$\frac{w + x}{a + b} = \frac{x}{b}$$

$$\therefore \qquad a\,x = b\,w.$$

Or we may proceed to find first the value of the current G, flowing through the galvanometer before balance is established, and then, by equating the result to zero, discover the relation existing between a, b, w, and x.

Thus, employing Kirchoff's two corollaries to Ohm's Law,[1] and denoting by A, B, W, X, and F, the currents flowing through a, b, w, x, and the battery branch respectively, we have (by first corollary)

$$\begin{aligned} A &= B - G \\ F &= A + W \\ W &= X + G \end{aligned}$$

and (by second corrollary)

$$\begin{aligned} a\,A - g\,G - w\,W &= o \\ g\,G - x\,X + b\,B &= o \end{aligned}$$

Eliminating A, W, X, and B from these five equations, we obtain the following equation, which expresses G in terms of the resistances of the various parts of the Bridge and of the current in the battery branch,

$$G = \frac{(b\,w - a\,x)\,F}{(a + b + x + w)\,g + (a + w)\,(x + b)} \qquad \ldots \qquad \ldots \qquad (c.)$$

Now, in order that G may be $= o$, either F must $= o$

or $$\frac{b\,w - a\,x}{(a + b + x + w)\,g + (a + w)\,(x + b)} \text{ must } = o$$

But F is not $= o$,

Therefore $$\frac{w\,b - a\,x}{(a + b + x + w)\,g + (a + w)\,(x + b)} \text{ must } = o$$

This fraction can vanish either by the numerator becoming $= o$, or by the denominator becoming $= \infty$;

But the denominator is not infinite,

And, therefore, when $G = o$,

$$a\,x = b\,w.$$

---

[1] *Vide* Appendix II.

III. *Unequal Branches.*—Were a and b always equal and incapable of change, it would not be possible, with such an arrangement as that referred to in paragraph I., to measure resistances smaller than 1 unit, or larger than 10,000 units; but, as b can be made larger than a, resistances exceeding 10,000 units can be measured, and as a can be made larger than b, resistances smaller than 1 unit can be measured.

For example, making $a = 10$, $b = 1000$, $w = 10{,}000$ (the highest resistance possible to unplug in the comparison coil), then, according to formula (1)

$$x = \frac{1000}{10} \times 10{,}000$$
$$= 1 \text{ million},$$

which is the greatest resistance that can be measured.

Again, making $b = 10$, $a = 1000$, and $w = 1$ (the lowest resistance available in the comparison coil), then, according to the same formula,

$$x = \frac{10}{1000} \times 1$$
$$= 0{\cdot}01$$

which is the smallest resistance that can be measured.

Thus the limits of measurement with the above testing arrangement are 0·01 unit and 1,000,000 units; and, between these limits, all resistances, which do not differ by quantities smaller than 1 unit in the comparison coil, can be measured—in all fifty thousand different resistances. This range will generally prove sufficient for all practical purposes.

We may observe that it is not practicable to make the resistances which it is possible to unplug in the comparison coil differ by an indefinitely small quantity, and hence *all* the resistances between the limits of measurement cannot be measured. If, however, instead of having the branch resistances and the comparison coil severally variable by fixed quantities, the comparison coil was kept variable by a fixed quantity, but the ratio of the resistances of the branch coils a and b was made to vary by having the point m movable between p and q, all resistances between the limits of measurement (theoretically *nothing* and *infinity*) could be measured. This latter form of the Bridge has been adopted in cases where it is required to measure accurately small fractions of a unit. The branches a and b are then represented by a platinum wire, along which the contact point m can be moved.

IV. *Balance cannot be accurately obtained.*—Sometimes, when measuring resistance very accurately, balance cannot be established exactly. In such a case, the resistance at which balance arrives may be calculated. For instance, two resistances are different from each other by unity; one is too small d°, the other is too large d'°. To obtain the real value of the unknown resistance approximately, $\frac{d}{d+d'}$ would be the fraction of the difference between the two resistances to be added to the smaller one, and $\frac{d'}{d+d'}$ similarly would have to be the subtracted from the higher resistance.

Example.—A given resistance x is to be measured as accurately as possible. We find that for $a = 1000$ and $b = 10$, $w = 560$ is 4° too small, while $w = 561$ is 6° too large.

Hence $\frac{4}{4+6} = 0{\cdot}4$ units is to be added to 560—or $\frac{6}{4+6} = 0{\cdot}6$ units is to be subtracted from 561—*i.e.*, we have the more accurate $w = 560{\cdot}4$, or $x = 5{\cdot}604$, which value may now be taken as correct to the 3d decimal place.

V. *Sensibility of the Method.*

§ 1. As the sensibility of Wheatstone's Bridge is greatest when the resistances in the four branches are equal, this condition should always be fulfilled as nearly as possible. For instance, when measuring a resistance of about 10 units, the branches a and b should be each made equal to 10 units, and so forth. The proper proceeding is this :—

If we have no idea about the magnitude of the unknown resistance to be measured, we ascertain that magnitude first by a rough measurement. After which we employ the right arrangement of the Bridge, and execute a second more accurate measurement of the unknown resistance.

This can be proved as follows.[1] By formula (*c.*) we have

$$G = \frac{bw - ax}{g\,(a + b + w + x) + (a + w)\,(b + x)}\,F$$

$$\left.\begin{array}{llll}\text{Substituting} & S & \text{for} & a + b + w + x \\ \text{,,} & s & \text{,,} & a + w \\ \text{,,} & t & \text{,,} & b + x\end{array}\right\}\text{Constants}$$

$$\left.\begin{array}{llll}\text{,,} & p & \text{,,} & \dfrac{a}{w} \\ \text{,,} & kp & \text{,,} & \dfrac{b}{x} \\ \text{,,} & q & \text{,,} & \dfrac{a}{b}\end{array}\right\}\text{Variables}$$

where k represents an absolute number between o and ∞, which becomes unity when balance is established or $G = o$,

Then
$$G = \frac{F}{gS + st}.\,k\,(k - 1)\,S^2.\,\frac{pq}{(kpq + kp + kq + 1)^2}$$

---

[1] This demonstration is given, as the author, although aware that the Law is well known, has never seen it proved anywhere.

in which expression the factor

$$\frac{pq}{(kpq + kp + kq + 1)^2} = Q \text{ is the only variable.}$$

It is true that F is also a function of p and q, but the Law of Sensibility is only of practical interest when balance is nearly attained, or when k nearly $= 1$, at which state F also is very nearly constant; and, therefore, to discover the condition of maximum sensibility, or the maximum value of G, near balance, we have only to consider the factor Q.

Thus $$Q = \frac{pq}{\{k(pq + p + q) + 1\}^2}$$

$$\frac{dQ}{dp} = \frac{q(kq + 1 - kpq - kp)}{\{k(pq + p + q) + 1\}^3} = \frac{qm}{n^3}$$

$$\frac{d^2Q}{dp^2} = \frac{q\{3k^2(q + 1)^2p - n(p + k) - 3k(q + 1)(kq + 1)\}}{n^4}$$

and $$\frac{dQ}{dq} = \frac{p(kp + 1 - kpq - kq)}{\{k(pq + p + q) + 1\}^3} = \frac{pm'}{n^3}$$

$$\frac{d^2Q}{dp^2} = \frac{p\{3k^2(p + 1)^2q - n(q + k) - 3k(p + 1)(kp + 1)\}}{n^4}$$

When $\frac{dQ}{dp} = o, m = o$

or, $kq + 1 - kpq - kp = o$

When $\frac{dQ}{dq} = o, m' = o$

or, $kp + 1 - kpq - kq = o.$

These two conditions, for the same value of k, can only be fulfilled by $p = q = \sqrt{\frac{1}{k}}$

or, when balance is attained, by $p = q = 1$

and substituting $p = q = 1$ in $\frac{d^2Q}{dp^2}$ and $\frac{d^2Q}{dq^2}$ they both become negative;

Hence $p = q = 1$ corresponds to the maximum of Q,

that is $p = q = 1$, or $\frac{a}{w} = \frac{a}{b} = 1$, or $w = b$, corresponds to a maximum of G when balance is nearly established; in exactly the same manner can be proved that $a = x$;

And as in the case of balance $\frac{a}{b} = \frac{w}{x}$

therefore $$a = b = w = x.$$

§ 2. The sensibility of the Bridge method also depends on the resistance of the galvanometer used, being greatest when the following relation exists between the resistance of the galvanometer and the four branch resistances:

$$g = \frac{(a + w)\,(b + x)}{a + b + w + x}$$

and therefore with the ordinary Bridges used in testing, with which resistances varying between 0·01 unit and 1,000,000 units can be measured, the best resistance of the galvanometer (*i.e.*, that corresponding to the mean resistance[1] when the Bridge is otherwise least sensitive) is 5455·4 units.

If a galvanometer have a system of coils which can be joined parallel or consecutively (by means of a commutator), that arrangement of the coils should be adopted which most nearly fulfils the above equation.

In order to raise the magnetic moment of a galvanometer in simple circuit to a maximum, the resistance of the galvanometer must be made equal to the external resistance.

By analogy it may be inferred that there must be a similar law in measuring resistances with Wheatstone's Bridge; and the only question is, which in this case is *the external resistance?*

The current G in the galvanometer, before balance is established, can be expressed by,

$$G = \frac{E}{g\dfrac{(x+w)(a+b)+f(a+b+w+x)}{bw-ax} + \dfrac{f(b+x)(a+w)+ab(x+w)+xw(a+b)}{bw-ax}}$$

where E is the E.M.F. of the testing battery, and f its resistance between p and q (Fig. 1).

Let us substitute

$$bw - ax = a$$

$$(x + w)(a + b) + f(a + b + w + x) = V$$

$$f(b + x)(a + w) + ab(x + w) + xw(a + b) = W$$

---

[1] The Bridge is least sensitive when high resistances are being measured, which require the most unequal branches to be used, *i.e.*, resistances from 100,000 to 1,000,000 units.

and multiplying the equation by U, the number of convolutions in the galvanometer-coil, we obtain its magnetic momentum Y,

$$Y = a\frac{U}{gV + W}E$$

The space to be filled with wire of known and constant conductivity being given, and calling q the sectional area of this wire, we have between U, q, and g the following two equations:—

$$U = \frac{\text{const.}}{q}$$

$$g = \frac{U\ \text{const.}}{q}$$

Therefore $$U = \text{const.}\ \sqrt{g}$$

and consequently $$Y = a\frac{\sqrt{g}}{gV + W}E\ \text{const.}$$

In this equation g only is taken as variable; and the question now is, what must be the value of g in order to raise Y to its maximum?

This will be the case when $g = \frac{W}{V}$, or, by substituting the values of W and V,

$$g = \frac{f(b + x)(a + w) + ab(x + w) + xw(a + b)}{(x + w)(a + b) + f(a + w + x + b)}$$

by dividing both numerator and denominator by ax, we obtain an equation better suited to our purpose,

$$g = \frac{f\left(1 + \frac{w}{a}\right)\left(1 + \frac{b}{x}\right) + wb\left(\frac{1}{a} + \frac{1}{x}\right) + w + b}{\left(1 + \frac{w}{x}\right)\left(1 + \frac{b}{a}\right) + f\left(\frac{w + b}{ax} + \frac{1}{a} + \frac{1}{x}\right)}$$

This equation establishes a general dependence between the resistance of the galvanometer and that of the other five branches, including the battery branch, when the magnetic moment of the galvanometer-coil is a maximum. The above equation, having been developed without reference to a balance, we must obtain the known law of simple circuit if we put $a = x = \infty$.

Thus $$g = f + b + w$$

which is the law for simple circuit, proving the general applicability of this equation.

Instead of the above equation we may put

$$g = \frac{ab}{a + b} + \frac{wx}{w + x} + f\gamma$$

which is identical with the other if

$$\gamma = \frac{(a\,x - b\,w)^2}{(a + b)\,(x + w)\{(a + b)\,(x + w) + f(a + b + x + w)\}}$$

But as it is evident that the law is of no practical interest unless balance is almost established, we have always $a\,x - b\,w$ very near zero; consequently γ, which is proportional to the square of $a\,x - b\,w$, must approximate still nearer to zero; and f, the resistance in the battery branch, being comparatively small, we may in this case, without sensible error, put

$$f\gamma + 0$$

hence we have approximately

$$g = \frac{a\,b}{a + b} \times \frac{w\,x}{w + x}$$

But as $(ax - bw)^2$ is indefinitely small, we may write

$$g = \frac{(a + w)\,(b + x)}{a + b + w + x}$$

This equation gives us the following simple law for Wheatstone's Bridge when near balance :—

To raise the magnetic moment of the galvanometer to its maximum, its resistance must be equal to the parallel resistance of the two double branches which are opposite to the galvanometer.[1]

And according to this, we can always calculate the proper resistance of the galvanometer, viz., the diameter of wire to be used when the space to be filled is given.

The above law gives us, for every new resistance to be measured, a new resistance of the galvanometer; but as the galvanometer can only have a very limited number of definite resistances, the law we have given must apply to those values to be measured *for which the other conditions are the most unfavourable;* and it is evident that in Line testing this will be the case for all large resistances, which can be measured only with a great difference in the branches a and b.

With the usual bridges generally applied in Line testing, we can measure resistances between $\frac{1}{100}$ and 1,000,000 units, having in the branches a and b the resistances 10, 100, and 1000; and in the comparison-coil, resistances variable from 1 to 10,000 units; and it is undeniable that, having to choose the resistance of a galvanometer with one coil only for this kind of Bridge, our law must apply to all resistances between 100,000 and 1,000,000 units, or to the average resistance 550,000.

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[1] We will mention here that this law is correct only when the sectional area of the insulating covering is always in the same proportion to q, the sectional area of the wire. But as the thickness of the insulating covering is generally the same for thick as for thin wires, this condition is never fulfilled in practice, especially with small galvanometers used in measuring large resistances. *Vide* Phil. Mag., May 1866 and Jan. 1867.

To measure 550,000 units we have to put in the equation

$$a = 10$$
$$b = 1000$$
$$w = 5500$$

and $$x = 550000$$

and then we have $$g = 5455{\cdot}4$$

For practical use it will be better to write the equation in the following form:

$$g = \left(\frac{a + w}{a + b}\right) b$$

which is identical with the other, because $ax - bw$ is indefinitely small.

§ 3. A bridge arrangement, besides the four branches, a, b, w, and x, has always two diagonals mn and pq (fig. 1), in one of which the galvanometer is situated, and in the other the battery; and it appears at first sight as if it is quite indifferent which of the diagonals is chosen for the reception of the galvanometer. Considering, however, the current which passes through the galvanometer before balance is rigidly established, and which current, in order to have the greatest sensibility, should be as large as possible, it can easily be proved[1]

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[1] The current G, which passes through the galvanometer before balance is obtained, if connected up in the diagonal pq (fig. 1), is

$$G' = E\frac{bw - ax}{N'}$$

where

$$N' = g\left\{(x + b)(a + w) + f(a + b + w + x)\right\} + f(w + x)(a + b) + aw(b + x) + bx(a + w)$$

While if the galvanometer is connected up in the diagonals mn, we have

$$G'' - E\frac{bw - ax}{N''}$$

that only one of the two diagonals, in any given case, should be chosen for the galvanometer branch.

If we call f the total resistance in the battery branch, and g the total resistance in the galvanometer branch, then the rule for choosing is the following:—

$$\left.\begin{array}{l} g > f \text{ the galvanometer} \\ g = f \text{ galvanometer or battery} \\ g < f \text{ the battery} \end{array}\right\} \begin{array}{l} \text{should be connected up} \\ \text{in that diagonal which} \\ \text{connects the junction of} \\ \text{the two smallest with} \\ \text{the junction of the two} \\ \text{largest branches.} \end{array}$$

Hence if the ascending order of magnitude of the four branches is a, b, w, x, and if $g > f$ (the general case in Line testing), the galvanometer ought to be connected up in the diagonal mn, but not in pq (fig. 1).

VI. *Natural Currents.*—Formula (1), for calculating the value of the resistance x, is only correct so long as there is but *one* electromotive force E in circuit, in which case the measurements made with positive and negative currents (the testing current reversed at the battery reverser u) will agree with one another within the limits of observation errors. As, however, in practice it frequently happens that the measurements made with

---

where

$$N'' = f\{(x + b)(a + w) + g(a + b + w + x)\} + g(w + x)(a + b) + aw(b + x) + bx(a + w)$$

Hence that of the two G is largest, for any constant E $(bw - ax)$ which has the smallest N.

If we subtract N'' from N' we get

$$N' - N'' = (g - f)(x - a)(w - b)$$

Now say that the ascending order of magnitude of the four branches is a, b, w, x, it follows that $(x - a)(w - b)$ is positive, and the sign of $N' - N''$ depends on the sign of $g - f$ only. Hence $N' - N''$ is positive, or $N' > N''$ if $g > f$; *i.e.*, we ought to connect up in this case the galvanometer in the diagonals mn, but not in pq (fig. 1).

the two currents differ to an extent not to be explained by errors of observation, but to be attributed to a *second* electromotive force which produces a natural[1] current in the resistance, it becomes necessary to develop formulæ in which this second electromotive force shall be taken into account.

Since we can only measure electrical resistance by observing the current which a known electromotive force produces through it, whether by methods direct, or, like the above, indirect, it is obvious, *à priori*, that, if a current already exist in the unknown resistance, independent of the testing current, the unknown resistance will appear to be smaller than it really is when the natural current flows in the same direction as the testing current, and larger than it really is when the natural current flows in the opposite direction. In the latter case the testing and the natural currents might even happen to be equal; under which circumstances no current would be observed, and the resistance would appear to be infinitely great. In any case, therefore, to obtain trustworthy results, it is necessary to measure with positive and negative currents; and for this reason a battery reverser is attached to each testing arrangement (fig. 1).

The following are the formulæ necessary for calculating the value of the unknown resistance when a natural current exists in it. As it is useful, and of theoretical interest, to know the magnitude of the electromotive force which causes the natural current, we shall also give formulæ for expressing this electromotive force in terms of that of the testing battery.

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[1] The currents which frequently exist in Telegraph Lines, and which are due to various causes, we shall always designate *natural* currents. This name, although not unobjectionable, is so to a less degree than the one ordinarily employed, viz., *earth* currents. For the latter are only a particular class of the currents which may exist in a Telegraph Line.

Let f be the resistance of the testing battery, e the unknown electromotive force, w' w'' the two resistances unplugged in the comparison coil when positive and negative currents are successively used,

Then

$$x = \frac{b f(a+b)\,(w'+w'') + b^2\,\{a(w'+w'') + 2\,w'\,w''\}}{a\,b\,(w'+w'') + 2\,a f\,(a+b) + 2\,a^2 b} \quad \ldots \quad (2)$$

$$\text{and } e = \frac{(w''-w')\,b}{(w'+w'')\,b + 2f\,(a+b) + 2\,a\,b}\,E \quad \ldots \quad \ldots \quad (3)$$

If we use equal branches, $a = b$

$$\therefore \ x = \frac{(w'+w'')\,(2f+a) + 2\,w'\,w''}{w'+w''+2\,(2f+a)} \quad \ldots \quad \ldots \quad \ldots \quad (4)$$

$$\text{and } e = \frac{(w''-w'}{w'+w''+2\,(2f+a)}\,E \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (5)$$

And if we neglect the battery resistance, $f = o$

$$\therefore \ x = \frac{b}{a}\,\frac{a\,(w'+w'') + 2\,w'\,w''}{w'+w''+2\,a}$$

$$= \frac{b}{a}\left\{\frac{w'+w''}{2} - \frac{(w''-w')^2}{2\,(w'+w'')+4\,a}\right\} \quad \ldots \quad \ldots \quad (6)$$

$$\text{and } e = \frac{w''-w'}{w'+w''+2\,a}\,E \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (7)$$

And, finally, if w'' differs but little from w'

$$x = \frac{b}{a}\,\frac{w'+w''}{2} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (8)$$

and $e = o$

The formulæ to be used are to be selected as circumstances may require. Thus, when the difference between w' and w'' is considerable, formulæ (2) and (3) must be used; if, at the same time, the battery resistance f is very small compared with the resistance to be measured, formulæ (6) and (7) may be used. Formulæ (4) and

(5) take the place of (2) and (3) when the branches are equal. When the difference between w' and w'' is very small, the arithmetic mean of the two resistances may be taken, as in formula (8).

The following calculations are given to illustrate formulæ 2, 6, 8, and 3, 7 :—

1. $a=1000$, $b=1000$, $w'=1000$, $w''=2000$, and $E=10$, $f=100$
By formula (4) $x=1407{\cdot}4$
,, (6) $x=1400$
,, (8) $x=1500$
,, (5) $e=\quad 1{\cdot}85$
,, (7) $e=\quad 2{\cdot}0$

2. $a=10$, $b=1000$, $w'=1000$, $w''=2000$, and $E=10$, $f=100$
By formula (2) $x=134{,}481$
,, (6) $x=133{,}444$
,, (8) $x=150{,}000$
,, (3) $e=\quad 3{\cdot}10$
,, (7) $e=\quad 3{\cdot}31$

3. $a=1000$, $b=10$, $w'=1000$, $w''=2000$, and $E=10$, $f=100$
By formula (2) $x=14{\cdot}8$
,, (6) $x=14$
,, (8) $x=15$
,, (3) $e=0{\cdot}397$
,, (7) $e=2{\cdot}0$

We thus see that, when measuring high resistances, formula (6) gives better results than formula (8), but with low resistances the reverse is the case; and that formula (7) must on no account be used, when small resistances are being measured.

Let e be the unknown electromotive force producing a current in x. First suppose the current in x to flow in the same direction as the testing current, and let w' be the resistance unplugged in the comparison coil when balance is established,

Then
$$A'=B'$$
$$X'=W'$$
$$F'=A'+W'$$

and

$$\begin{aligned} a\,A' - w\,W' &= o \\ x\,X' - b\,B' &= o \\ f\,F' + a\,A' + x\,X' &= E + e \end{aligned}$$

whence

$$\frac{b\,(a + f) + a\,(x + f)}{a\,x - b\,w'} = \frac{e + E}{e} = 1 + \frac{E}{e} = 1 + y$$

or, $$a\,(b + f) + b\,(w' + f) = y\,(a\,x - w'\,b) \qquad \ldots \qquad \ldots \qquad (d)$$

Now suppose the current in x to flow in the opposite direction to the testing current, that is reversing the testing current by means of the commutator u, and calling w'' the resistance unplugged in the comparison coil when balance is established,

Then

$$\frac{b\,(a + f) + a\,(x + f)}{a\,x - b\,w''} = \frac{e - E}{e} = 1 - \frac{E}{e} = 1 - y$$

or, $$a\,(b + f) + b\,(w'' + f) = y\,(b\,w'' - a\,x) \qquad \ldots \qquad \ldots \qquad (e)$$

Combining (d) and (e)

$$x = \frac{b\,f\,(a + b)\,(w' + w'') + b^2\,(a\,w' + 2\,w'\,w'' + a\,w'')}{a\,b\,(w' + w'') + 2\,a\,f\,(a + b) + 2\,a^2\,b}$$

and

$$e = \frac{b\,(w'' - w')}{(w' + w'')\,b + 2\,f\,(a + b) + 2\,a\,b}\,E$$

The following is an investigation of the errors introduced by the use of the more simple but less accurate formulæ :—

Writing $$s \text{ for } \frac{w' + w''}{2}$$

and $$\Delta \text{ for } \frac{w'' - w'}{2}$$

we have $$x = \frac{b}{a}\left\{ s - \frac{\Delta^2}{a + s + f\,(1 + \frac{a}{b})} \right\}$$

Hence by neglecting the battery resistance, that is by putting $f = o$, the second term of the right-hand member of this equation becomes too large, and we obtain a value of x, which is too small.

Again, by taking simply the arithmetic mean of the two resistances w' w'', that is by neglecting the second term of the right-hand member of this equation, so long as Δ is greater than zero, *i.e.*, w' differs from w'', we get x too large.

Making similar substitutions in the equation for e, we have

$$e = \frac{b}{a} \frac{\Delta}{b\left(\frac{s}{a} + 1\right) + f\left(1 + \frac{b}{a}\right)} E$$

if we neglect the battery resistance, *i.e.*, put $f = o$, we obtain a value of e, which is too large.

VII. *Testing the Correctness of the Bridge.*—The bridge arrangement should be tested for correctness every day, as follows:—

1. Make $x = o$, $w = o$ (all stoppers in), $a = b = 10$, balance should now be undisturbed.
2. Making $w = 1$ and leaving the other resistances as before, the needle must be deflected in such a direction as to show w too large.
3. Make $x =$ *infinity* (opening the circuit), and an opposite deflection must take place.
4. Make $x = w =$ *infinity* and $a = b = 1000$, and balance should again be established.

The insulation resistance of the testing arrangement should always be more than 1 million (*i.e.*, higher than the highest resistance to be measured). In damp weather it may occur that this is not the case, and that, even after cleaning and carefully removing as much moisture as possible from the apparatus, the resistance is still too low. Under such circumstances, before and after each insulation test, the resistance of the apparatus must be measured, and, if necessary, taken into account as follows:—

Supposing the insulation of the testing arrangement

$= I$, the insulation of the line and the testing arrangement $= i$, and the insulation of the line $= x$,

then $$i = \frac{I\,x}{I + x} \text{ or } x = \frac{i\,I}{I - i}$$

For instance, if $i = 0{\cdot}32$ million

$I = 0{\cdot}82$ million

then $$x = \frac{0{\cdot}32 \times 0{\cdot}82}{0{\cdot}82 - 0{\cdot}32} = 0{\cdot}525 \text{ million.}$$

VIII. *Measuring the Resistance of the Galvanometer.*—It may occasionally be required to measure the resistance of the Bridge galvanometer, when a second galvanometer is not at hand. The following method, due to Sir William Thomson, is the best. Introduce the galvanometer in the place of the unknown resistance, and, between p and q, in the place of the galvanometer, put a key.

Close the circuit at 1, and note the deflection of the galvanometer needle: then, if, on pressing down the key between p and q, the deflection remain unaltered,

$$g = \frac{b}{a} w \text{ [1]}$$

It will generally be found necessary, on account of the great sensibility of the galvanometer, to make b larger than a in order to obtain a readable deflection, or even to shunt the galvanometer by a resistance which is known.

Example.—The resistance of a galvanometer is to be measured by the above method. The resistance is marked = 1350 B.A.U. at 80° Fahr. The needle is astatic, and the galvanometer highly sensitive. Our first endeavour must be to make the arrangement in such a manner that we can measure the current sufficiently accurate which passes through the galvanometer. Making $a = b = w = 1000$ we find the needle is deflected to 90°. We then reduce the testing battery to *one* cell only, but find that the current is still too strong for accurate measurements (the needle still points to 90°, although not with such a great force as in the first case). We then make $b = 1000$ and $a = w = 10$, and find that although the deflection has decreased to 82°, it is still too large for accurate measurement. Hence we can do nothing else but shunt the galvanometer, by a resistance r, which accurately measured beforehand gave 990 B.A.U. We now find that for $w = 5$ the deflection becomes 55°, and when pressing the key this deflection becomes 50°, while for $w = 6$ the deflection becomes 54°, which, on pressing the key, is increased to 56°. Thus we know that w, at which perfect balance would have arrived, *i.e.*, at which the pressing of the key would have made no alteration in the deflection of the needle, is situated somewhere between 5 and 6 units. But by the first reading we know that $w = 5$ is 5° too small, and by the second reading we know that $w = 6$ is 2° too large, hence $w = 5{\cdot}71$ approximately.

---

[1] This is obvious, for if making the resistance between p and q *infinite* and *zero* does not alter the currents in the branches of the bridge, it follows that no current passes between p and q, *i.e.*, balance is established, hence $g = \frac{b}{a} w$.

Therefore the parallel resistance of the galvanometer (g) and the shunt (r) is

$$\frac{g\,r}{g+r} = \frac{b}{a}\,w = \frac{1000}{10}.\ 5{,}71. = 571.$$

Hence $g = 1349$ B.A.U. at 80° Fahr., the temperature of the room when the measurement was made.

IX.—*Best Practical Arrangement of the Bridge.*

§ 1. *Resistance of the Galvanometer.*—It is quite convenient to make a galvanometer with *two* coils which, by means of a commutator, can be either used connected up successively or parallel.

Be the resistance of these two coils g' and g'', thus it can be proved they should be

$$g' = 1000$$
$$g'' = 4000$$

in order to have

$$g = g' + g'' = 5000 \text{ (coils connected successively),}$$

and $g = \dfrac{g'\,g''}{g' + g''} = 800$ (coils connected parallel).

$g = 5000$ should be used only when measuring the high resistances $x \geqq 10{,}000$, *i.e.*, when using the branches $a = 10$ and $b = 1000$, or $a = 100$ and $b = 1000$.

$g = 800$ should be used when measuring all the other resistances $x \leqq 10{,}000$.

§ 2. *Position of the Galvanometer.*—When using the branches $a = b$ or $a < b$ the galvanometer is to be in the diagonal $m\,n$ (Fig. 1). (This is the case in line testing.)

When using $a > b$, the galvanometer is to be in the diagonal pq (Fig. 1). Hence a commutator must be provided for this change (Fig. 2).

§ 3. *E.M.F. of the Testing Battery.*—To be able to measure all the resistances x between 0·01 and 1 Ω, with about the same relative average sensitiveness, *i.e.*, each x to be measured within the same percentage of accuracy—by any given galvanometer, and without altering the sensitiveness of such galvanometer—it can be proved that the following E.M.F.'s are requisite :—

Resistances above 100,000 ; $E = 100\,e$
Resistances above 10,000 ; $E = 10\,e$
All resistances under 10,000 ; $E = e$

The galvanometers used in connection with a bridge are generally so sensitive, that $e = 1$ volt (say a Daniell) will be found more than sufficient ; hence the testing battery should consist of 1, 10, and 100 Daniell's, and for which purpose a battery commutator is required (Fig. 2).

In Fig. 2 the diagram of such a bridge arrangement is given, and Fig. 3 the actual plan.

X. *Measuring the Constants of the Testing Battery.*—A convenient method for measuring the constants of the testing battery with any galvanoscope employed for testing with the bridge is the following :—

Bring the galvanoscope in the diagonal pq. (See Fig 1.)

§ 1. *Measurement of Resistance.*—

Make

$$b = \infty$$
$$x = o$$

and get a readable deflection by putting

$$a = a'$$
$$w = w'$$

and then get the same deflection, by using two other values for a and w, namely,

$$a = a''$$
$$w = w''$$

Then, as can be easily proved, we have

$$f = a'' \frac{\left(\frac{g}{w''} + 1\right) - a'\left(\frac{g}{w'} + 1\right.}{g\left(\frac{1}{w'} \quad \frac{1}{w''}\right)}\Bigg) \quad \ldots \quad (9)$$

If we can take the first reading with $a' = o$, we have more simple

$$f = \frac{a''\,(g + w'')}{g\left(\frac{w''}{w'} - 1\right)}$$

Or as g is generally very large, and on account of the galvanometer being very sensitive, w'' very small, we may in most cases neglect w'' against g, when approximately we have

$$f = \frac{a''}{\frac{w''}{w'} - 1}$$

This method for measuring the resistance of the battery has a sufficiently large range, for we are able to give to a the following values, 0, 10, 100, 110, 1000, 1100, 1110; and for w the value from 1 to 10000. Besides, by using a permanent magnet for influencing the needle of the testing instrument, we can make the same as unsensitive as a proper reading of any current requires it.

§ 2. *Comparison of E.M.F.*—To compare the E.M.F. of the testing battery with that of the standard cell (see further on), we can use exactly the same method as given before; *i.e.*, we get a readable deflection with the E.M.F. to be expressed in terms of the standard, and then get the same reading with the standard cell. We will call E, the E.M.F. of the testing battery, and e, that of the standard cell.

Further, be F the resistance of the testing battery, and f that of the standard—both we know by former trials—and suppose for

$$a = a'$$

and $$w = w'$$

we get a deflection α° with E, and for

$$a = a''$$

and

$$w = w''$$

we get the same deflection α° with e; then, as can easily be proved, we have

$$\frac{E}{e} = \frac{\left(F + a'\right)\left(\frac{g}{w'} + 1\right) + g}{\left(f + a''\right)\left(\frac{g}{w''} + 1\right) + g} \quad \ldots \quad \ldots \quad (10)$$

Or suppose that the galvanometer has been adjusted so unsensitive that we could take the reading with e for

$$w'' = \infty$$

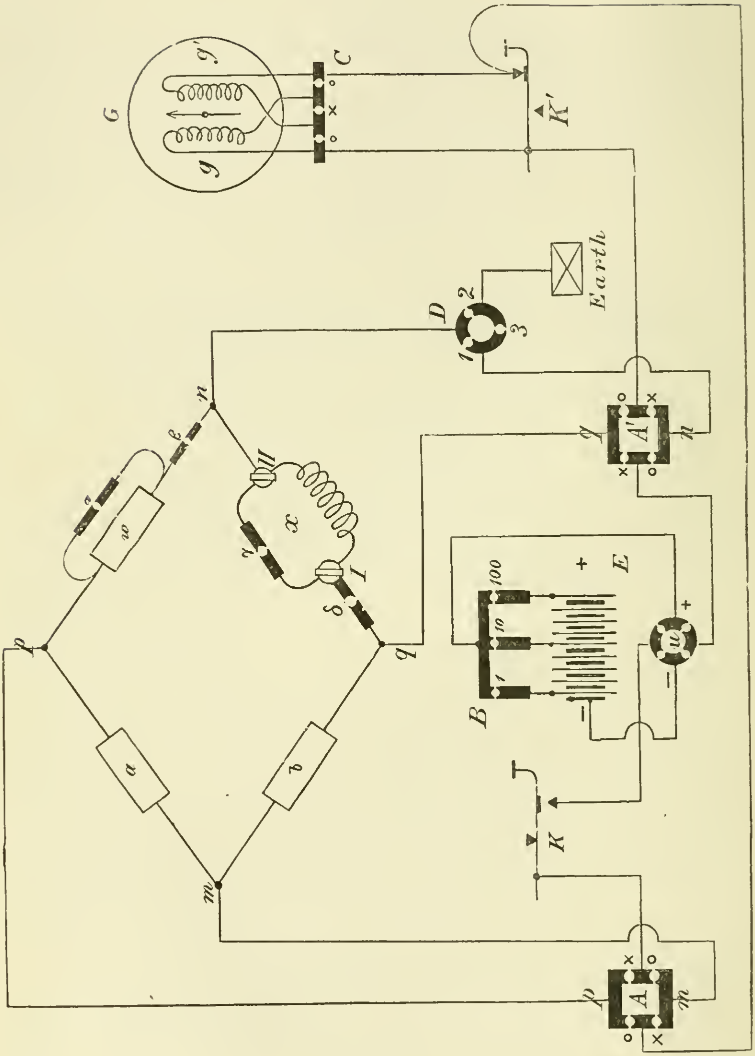
and

$$a'' = o$$

then

$$\frac{E}{e} = \frac{\left(F + a'\right)\left(\frac{g}{w'} + 1\right) + g}{f + g}$$

Fig. 2.



Explanation of the Diagram.

G a sensitive galvanometer with coils g and g'.

$g = 4000$ units and $g' = 1000$ units resistance.

C a commutator, by which the coils can be connected up successively or parallel.

Stopper in X only, we have $g + g' = 5000$ units.

Stoppers in *oo*, we have $\frac{g\,g'}{g + g'} = 800$ units.

K' a key, which short circuits the galvanometer.

B the battery commutator, by which 1, 10, and 100 cells can be selected.

E the electromotive force of the testing battery, consisting of 100 cells successively connected.

K a key for closing the battery branch.

A and A' commutators for changing the position of the galvanometer with respect to the diagonals.

Stoppers in XX, XX. Galvanometer is in the diagonal *mn*, and the E.M.F. in diagonal *pq*.

Stoppers in *oo*, *oo*, the reverse takes place.

u an ordinary battery reverser.

w an ordinary resistance box of 1 to 10000 units.

a and b the branch resistances, each containing 10, 100, and 1000 units.

α and γ arrangements for making w and $x = 0$ (by a single contact or stopper).

β and δ arrangements for making w and $x = \infty$ (by a single contact or by stopper).

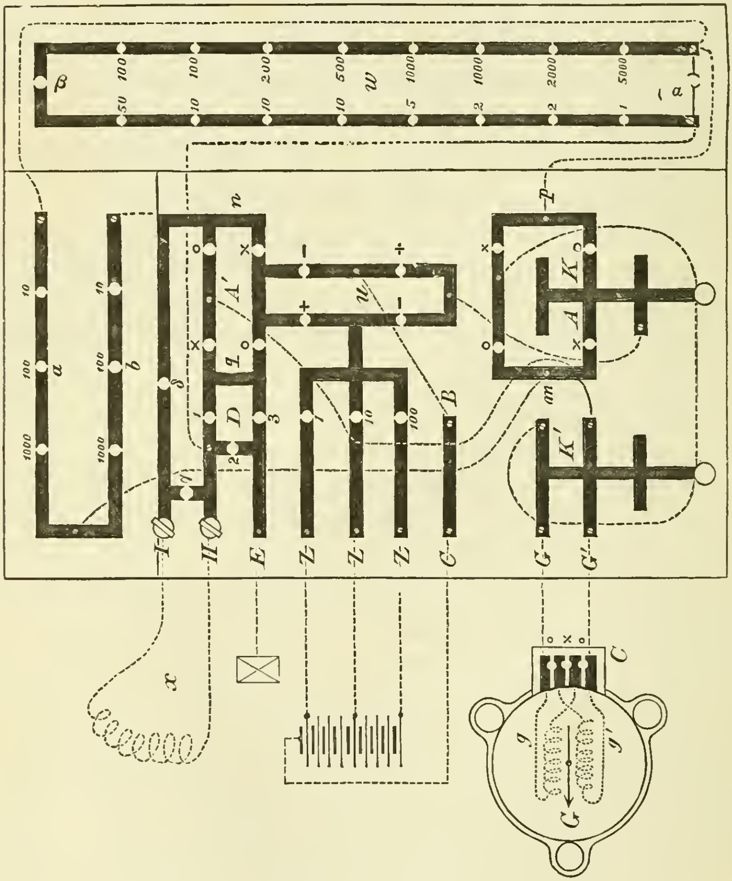
D a commutator required to measure resistances through the earth, as is the case when one end of the line only can be brought in connection with the bridge, the other end being put to earth. For instance—

Stopper 1 in, 2 and 3 out—resistances can be measured of which *both* the ends are in the testing office and earth is then off battery and bridge.

Stoppers 2 and 3 in, 1 out—a resistance can be measured of which only *one* end is at the testing office, and this must be connected to *I*.

Stopper 3 in, 1 and 2 out—localising faults by loop-test.

Fig. 3.



SECTION II.

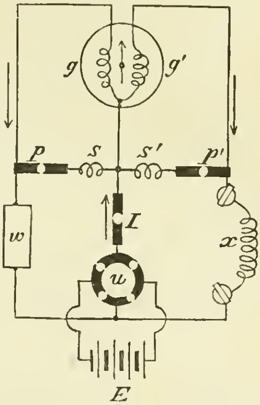
THE DIFFERENTIAL GALVANOMETER.

I. *Explanation of the Diagram.*—Fig. 4 gives a diagram of the differential arrangement as generally used.

G is a galvanometer having two coils $g\ g'$ wound so as to produce, with equal currents, equal but opposite effects on the needle.

s and s' are shunts, having resistances $\frac{g}{99}$ and $\frac{g'}{99}$, which can be applied to the coils $g\ g'$ respectively by inserting plugs at p and p'; they merely serve to carry off current from the coils, and have in themselves no action on the needle.

Fig. 4.



w is a comparison coil similar to that used in Wheatstone's Bridge.

x is the unknown resistance to be measured.
E is the electromotive force of the battery.
1 is a key, and u a battery reverser.

II. *Explanation of the Method.*—When the circuit is closed by pressing down the key at 1, the current entering G is divided, one portion of it flowing through g and w, and the other portion through g' and x, back to the battery, therefore the needle will be deflected to the one side or to the other according to which current is the stronger. But if the two currents be of equal strength *the needle will remain at rest.* Now in order to have the two currents equal, the total resistance in the one branch must be equal to the total resistance in the other branch. In practice the resistances of the two coils, g g', are made equal; and, therefore, to have the two currents equal, we must make w equal to x.

Hence, when on closing the circuit the needle remains at rest,

$$x = w.$$

III. *Using Shunts.*—If, in obtaining balance, both the shunts s and s' had been used, the formula expressing x would become:

$$x = \frac{1 + \frac{g}{s}}{1 + \frac{g}{s'}} w \quad \cdots \quad \cdots \quad \cdots \quad (1')$$

Now if s is made $= \frac{g}{99}$ and s' is made $= \infty$

$$x = 100\ w$$

and if s' is made $= \frac{g}{99}$ and s is made $= \infty$

$$x = 0{\cdot}01\ w$$

Thus by using the shunt s and making $w = 10{,}000$, we are enabled to measure 100 × 10,000 = 1 million units, and by using the shunt s' and making $w = 1$, we are enabled to measure 1 × 0·01 = 0·01 unit.

The range of measurement, therefore, is from 0·01 unit to 1,000,000 units: the same as with the Bridge.

IV. *Balance cannot be accurately obtained.*—Also here, like in the case of the Wheatstone's Bridge, it may happen that balance, by altering the comparison coil w *one* unit, cannot be accurately obtained. Then taking readings of the two deflections (right and left to the zero), we can calculate approximately, in exactly the same manner as before, the fraction of the unit which, added to the lower limit or subtracted from the higher limit, would give that value of w which produces perfect balances. An example is not required.

V. *Sensibility of the Method.*—The sensibility of the differential galvanometer is greatest[1] when the measured resistance x is equal to w the resistance in the comparison coil, *i.e.*, when no shunts are used. Hence we should always endeavour to measure an unknown resistance without the employment of shunts, and only use them when either x is larger than 10,000 or when it is required to know the value of x within fractions of a unit.

§ 2. The sensibility of the differential galvanometer also depends on the resistance of the coils of the instrument being greatest, if the following simple relation holds good between the resistance of the coil and the resistance to be measured :—

---

[1] This is obvious, and can be proved in a similar manner as it was done for the bridge. The differential galvanometer without shunts can be compared to a balance with equal arms, while with shunts it represents a balance of unequal arms.

$$g = \frac{w}{3}$$

w being the resistance to be measured.

As it is impossible to alter g for any resistance to be measured, w necessarily represents a certain average value of all the different resistances to be measured. Say for instance that the limits of measurement are 0 and 10,000 (without the use of shunts), and that the usual comparison coil $\frac{1}{10,000}$ is available, then the average would be 5000. However, it may be reasoned that this average is still too low, since clearly the maximum sensitiveness of the instrument is much more required for the upper than for the lower half of the resistances. Hence a better value for w would be the mean of the average and the high limit, which gives

$$w = \frac{5000 + 10,000}{2} = 7500$$

and therefore $g = \frac{7500}{3} = 2500$

This is a very good practical value.[1]

In all differential arrangements, with the exception of Wheatstone's Bridge, two coils of insulated wire, through each of which a current passes, are made to act simultaneously on the same movable magnet or system of magnets in opposite directions. They consequently neutralise one another's effect partially or wholly, as the case may be. The principle of testing with such an arrangement is to make the action of the two coils equal, that is to bring the magnet or system of magnets back to the zero point as indicated when no current was passing.

Balance may be established in two different ways—either by keeping the currents constant but altering the position of the coils with respect to the magnet, or by having the coils fixed but altering the relative strengths of the currents.

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[1] For a closer reference on this subject consult Journal Asiatic Society of Bengal, Vol. XLI. Part ii. p. 141, 1872; Phil. Mag., Vol. XLIV. p. 161.

The formula, however, for expressing the relation which exists between the known and unknown quantities after balance has been established, is independent of the method adopted in obtaining it. This will be better understood from what follows.

The plugs p and q being inserted, and the circuit closed at 1, the current which flows through the coil g is:

$$G = F. \frac{x + \dfrac{s' g'}{s' + g'}}{x + w + \dfrac{s g}{s + g} + \dfrac{s' g'}{s' + g'}} . \frac{s}{s + g}$$

F being the current in the battery branch. And the current which flows through the coil g' is:

$$G' = F. \frac{w + \dfrac{s g}{s + g}}{x + w + \dfrac{s g}{s + g} + \dfrac{s' g'}{s' + g'}} . \frac{s'}{s' + g'}$$

When balance is established we have

$$m G = m' G'$$

or

$$\frac{G}{G'} = \frac{m'}{m} = k \text{ suppose}$$

$m\, m'$ being respectively the magnetic moments of the coils $g\, g'$ for the unit of current. k is, therefore, the ratio of their magnetic moments, and is generally called the *constant* of the differential arrangement: it is an absolute number expressing how much more one coil acts than the other when equal currents are passing through them.

Substituting the values of G and G', we have

$$\frac{x + \dfrac{s' g'}{s' + g'}}{w + \dfrac{s g}{s + g}} . \frac{s}{+ g} . \frac{s' + g'}{s'} = k$$

Therefore $$x = \frac{k \left\{ w \left(1 + \dfrac{g}{s} \right) + g \right\} - g'}{1 + \dfrac{g'}{s'}}$$

which expression is quite independent of the method by which balance has been obtained.

If by moving one coil, or the other, or both, then k is a variable number, which for each position of the two coils must be known, and to discover which we must either have recourse to a table of constants specially prepared for the instrument we are using, or we must ourselves make a fresh determination.

As, however, the differential instruments generally used have fixed coils, and balance is established by altering the currents $G\,G'$, either by interposing resistance by means of the comparison coil, or by diminishing the action of one or other of the currents by means of variable shunts, k is for each instrument a constant; and, further, if the two coils have equal (but opposite) magnetic moments, $k = 1$.

Putting $k = 1$ in the general expression for x, we get the formula applicable in our case, namely,

$$x = \frac{1 + \frac{g}{s}}{1 + \frac{g'}{s'}}\, w$$

VI. *Natural Currents.*—Here, also, as in the case of Wheatstone's Bridge, we must develop formulæ for finding the true values of x, when there is a natural current in the resistance to be measured, and of the electromotive force e producing it.

The formulæ are, taking $g' = g$,

$$x = \frac{(w' + w'')\,\{g + f\,(n + n')\} + 2\,n\,w'\,w''}{2\,\frac{n'}{n}\left\{ g + f\,(n + n') \right\} + n'\,(w' + w'')} \quad \ldots \; (2')$$

and $$e = \frac{n\,(w'' - w')}{2\,\{g + f\,(n + n')\} + n\,(w' + w'')}\,E \quad \ldots \quad \ldots \; (3')$$

where $w'\,w''$ are the resistances unplugged to obtain balance, when positive and negative currents are successively used; and $n\,n'$ represent the multiplying power of the shunts, *viz.*:

$$n = 1 + \frac{g}{s}$$

$$n' = 1 + \frac{g}{s'}$$

n and n are generally powers of 10; and since, as already stated, s and s' are made equal to $\frac{g}{99}$ in the galvanometer generally used, we have $n = n' = 100$. When no shunts are used, $n = n' = 1$,

$$\therefore\ x = \frac{(w' + w'')\,(g + 2f) + 2\,w'\,w''}{2\,(g + 2f) + w'\,w''} \quad \cdots \quad \cdots \ (4')$$

and
$$e = \frac{w'' - w'}{2\,(g + 2f) + w' + w''} \quad \cdots \quad \cdots \quad \cdots \ (5')$$

when g' only is shunted, $n = 1$

$$\therefore\ x = \frac{(w' + w'')\,\{g + (n' + 1)\,f\} + 2\,w'\,w''}{2\,n'\,\{g + (n' + 1)\,f\} + n'\,(w' + w'')} \quad \cdots \ (6')$$

and
$$e = \frac{w'' - w'}{2\,\{g + (n' + 1)\,f\} + w' + w''} \quad \cdots \quad \cdots \ (7')$$

when g only is shunted, $n' = 1$

$$\therefore\ x = \frac{(w' + w'')\,\{g + (n + 1)\,f\} + 2\,n\,w'\,w''}{\frac{2}{n}\left\{g + (n + 1)\,f\right\} + w' + w''} \quad \cdots \ (8')$$

and
$$e = \frac{n\,(w'' - w')}{2\left\{g + (n + 1)\,f\right\} + n\,(w' + w'')} \quad \cdots \ (9')$$

Referring to figure 2, and denoting by large letters the currents, and by small letters the resistances through which they respectively flow, we have, by Kirchoff's corollaries, the following seven equations:

$$\begin{aligned} W &= G + S \\ X &= G' + S' \\ F &= G + G' + S + S' \\ g\,G - s\,S &= o \\ g'\,G' - s'\,S'' &= o \\ f\,F + g\,G + w'\,W &= E \\ f\,F + g'\,G' + x\,X &= E + e \end{aligned}$$

where E is the electromotive force of the testing battery, and e is the unknown electromotive force in x.

From these equations we have

$$\frac{f\left\{\frac{G}{G'}\,n + n'\right\} + g' + n'\,x}{f\left\{\frac{G}{G'}\,n + n'\right\} + \frac{G}{G'}\,(g + n\,w')} = 1 + \frac{e}{E} = 1 + y$$

Further, at balance, we have

$$\frac{G}{G'} = \frac{m'}{m} = k$$

Hence, at balance,

$$\frac{f(k\,n + n') + g' + n'\,x}{f(k\,n + n') + k\,(g + n\,w')} = 1 + y$$

Reversing the testing battery, we obtain similarly

$$\frac{f(k\,n + n') + g' + n'\,x}{f(k\,n + n') + k\,(g + n\,w''} = 1 - y$$

Developing x and y from these two equations, we have

$$x = \frac{2\{f(kn + n') + gk\}(gk - g') + nk[(w' + w'')\{f(kn + n') + 2gk - g'\} + 2nkw'w'']}{2\,n'\,\{f(k\,n + n') + g\,k\} + k\,n\,n'\,(w' + w'')}$$

and $$e = \frac{n\,k\,(w'' - w')}{2\,\{f\,(n\,k + n') + g\,k\} + n\,k\,(w' + w'')}\,E$$

From these formulæ we obtain those applicable in the case of our instrument, by putting $g' = g$ and $k = 1$, thus

$$x = \frac{(w' + w'')\,\{g + f\,(n + n')\} + 2\,n\,w'\,w''}{2\,\frac{n'}{n}\{\,g + f\,(n + n')\,\} + n'\,(w' + w'')}$$

and $$e = \frac{n\,(w'' - w')}{2\,\{\,g + f\,(n + n')\,\} + n\,(w' + w'')}$$

VII. *Testing the Correctness of the Differential Galvanometer.*—The differential arrangement should be tested for correctness before use as follows :—[1]

1. $x = o$, $w = o$, and $x = \infty$, $w = \infty$; with *both* Shunts or *no* Shunts, there should be balance.

2. $x = o$, $w = \infty$, and $x = \infty$, $w = o$; with *both* Shunts or *no* Shunts, there should *not* be balance. The two deflections obtained should be strong, and in opposite directions.

3. $x = o$, $w = 1$; with both Shunts. Note the deflec-

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[1] The influence of low insulation of the differential instrument is to be eliminated in the same manner as given for the bridge.

tion, a°——Put $w = 1$ in the place of $x = o$, and $x = o$ in the place of $w = 1$. The same deflection a° should be obtained, only in the opposite direction.

4. $x = o$, $w = 10{,}000$; with shunt on side of x. Note the deflection, b°——Put $w = 10{,}000$ in the place of $x = o$, and $x = o$ in the place of $w = 10{,}000$. The same deflection b° should be obtained, only in the opposite direction.

VIII. *Measuring the Resistance of the Differential Galvanometer.*—It may be required to measure the resistance of the Coils and Shunts of the Differential Galvanometer when a second comparison coil is not available. The following is a simple method:—*vide* Fig. 2.

Make $E = 1$ element of known resistance f.
$x = o$
and $w = w'$, such a resistance as to give a readable deflection.
Again, make $E = 1$ element.
$x = \infty$
and $w = w''$, such a resistance as to give the same deflection as before, only in the opposite direction, if the battery poles have not been reversed.

Then

$$g = -f + \sqrt{(w' w'' + f^2)}[1] \quad \dots \quad \dots \quad (10)$$

or, if f is very small compared with g,

$$g = \sqrt{w' w''}$$

From the same formula we get the value of the parallel resistance of coil and shunt, by making the two measurements with the shunt-plugs in. In this case f cannot be neglected.

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[1] I do not give the development, as the reader should do this himself.

From these two results the multiplying power of the shunts can be calculated, *viz.*: $\dfrac{1}{1 + \dfrac{g}{s}}$.

Example.—By the above method the resistance of the differential galvanometer, marked 2490 B.A.U. at 80° Fahr., is to be measured as well as the resistance of the shunt.

Readings without Shunts.—E.M.F. = 1 minotti, with an internal resistance = 10 B.A.U.

For $x = o$ we find $w' = 1500$ (45° deflection), for $x = \infty$ we find that the deflection for $w' = 1500$ is 80°, and we therefore increase w', until for $w'' = 4166$ we get the same deflection (45°).

Therefore $g = -10 + \sqrt{1500 \times 4166 + 100} = 2489{\cdot}8$.

Readings with the Shunts.—For this case we find that in order to have sufficient sensitive readings we must use ten cells for the testing battery, which has an internal resistance = 100.

For $x = o$ we get $w' = 30$ (40° deflection), and for $x = \infty$ we get $w'' = 187$ (40° deflection).

Thus we have

$$\frac{s\,g}{s + g} = -100 + \sqrt{30 \times 186 + 10{,}000} = 24{\cdot}8,$$

and using $g = 2489{\cdot}8$ we get $s = 25{\cdot}05$

or $\dfrac{1}{1 + \dfrac{g}{s}} = \dfrac{1}{100{\cdot}39}$ as the multiplying power of the shunts.

In these experiments it has always been supposed that we know the resistances of the two galvanometer coils are equal; also the two shunts.

IX. *Best Practical Arrangement of the Differential Galvanometer.*—Also here, like in the case of the Wheatstone Bridge, an arrangement may be designed which will approach the bridge in sensitiveness and have the same range. An attempt of doing so, however, will show at once how complicated and expensive such an arrangement would be. For not only would the differential galvanometer be far more bulky and expensive than the instrument required for the bridge, but it would also be necessary to have recourse to *four different* shunts on each side of the differential galvanometer, in order to be able to obtain the multiplying powers (10 and 100) for the *two* different resistances of the instrument, which the approximate fulfilment of the law of sensitiveness necessitates. Further, the commutator for varying the resistance of the instrument (to connect the two coils on each side either successively or parallel) would also be more complicated and expensive than the one required for the bridge galvanometer, and with all this complication and additional expense we would still have a method much inferior to the bridge, especially with reference to sensitiveness and accuracy. Hence it is thought useless to give such a design in these instructions. Whenever a line-testing arrangement is requisite, a bridge of the given design should invariably be chosen.

X. *Measuring the Constants of the Testing Battery.*—The following is a convenient method :—

§ 1. *Resistance of Battery.*—Send the current of the testing battery through *one* side of the differential galvanometer with shunt in circuit. Then get a readable deflection ($\alpha' = 45°$ is best) by varying w. Be the resistance unplugged in the comparison coil w', in order to have a readable deflection $\alpha'°$.

After this send the current of the testing battery through both sides of the differential galvanometer (with the shunts in circuit) successively, and in such a manner that the one coil is adding its effect to the other. Then the deflection observed (α'') will be larger than in the first case (α').

Now increase w' until

$$\alpha'' = \alpha'$$

Be w'' the value of w, for which $\alpha'' = \alpha'$, then calling f the resistance of the battery, we have

$$f = w'' - 2\,w'^{\,1} \qquad \ldots \qquad \ldots \qquad (11)$$

Or if the differential galvanometer is so unsensitive, or the battery so weak, that the first deflection α' is readable for $w = o$, we have

$$f = w''$$

§ 2. *E.M.F. of the Testing Battery.*—Send the current of the testing battery of E.M.F. = E, and internal resistance = F, through the one side of the differential galvanometer (with shunt in circuit).

Note a readable deflection α', for $w = w'$, unplugged in the comparison coil.

Insert in place of the testing battery the standard cell of E.M.F. = e and internal resistance = f, and find $w = w''$, for which the deflection α'' is the same as α'. Then, as can be easily proved, we have

$$\frac{E}{e} = \frac{w' + F + \dfrac{g\,s}{g + s}}{w'' + f + \dfrac{g\,s}{g + s}} \qquad \ldots \qquad \ldots \qquad (12)$$

f and F are known by previous experiment, and $\dfrac{g\,s}{g + s}$ is also known.

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[1] Appendix III.

APPENDIX I.

OHM'S LAW.

Dr. S. J. Ohm published his celebrated book, "Die Galvanische Kette, Mathematisch bearbeitet,"[1] as early as 1827, at Berlin, in which he gave the general differential equation for the propagation of electricity through prismatic bodies; and from this equation he deduced the very simple law which justly bears his name, and which has been of such paramount importance in almost all subsequent discoveries in electrical science.

Ohm's Law is generally given as an experimental one, and although when once known it is simple enough to verify its truth by experiment, it was nevertheless *predicted* by Ohm from merely mathematical considerations based on a few experimental facts only.

This investigation is of great historical value, and must be of the highest interest to every earnest student. We, therefore, take this opportunity of giving an extract in free translation from the original development.

We shall only presume that the reader is already familiar with the electrical term "Potential" (which Ohm called "Electroscopische Kraft"[2]).

Ohm based his reasoning on the following three fundamental laws, of which one only is partially hypothetical, while the other two are purely experimental:—

1. The mode of propagation of electricity through any body is from one molecule to the next, indefinitely near to it, and is not direct between any two molecules that are at a finite distance from each other.

   The quantity of electricity transferred at any time between two such indefinitely near molecules is, in all cases and under all circumstances, proportional to the difference of the potentials of the two molecules, and to the time interval during which these potentials may be considered to remain constant.

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[1] "The Galvanic Circuit mathematically considered."

[2] "Electroscopic energy."

2. The loss of electricity by a uniformly charged body in a given time is (as proved by Coulomb) proportional to the surface of the body in contact with the surrounding medium, to the potential at the surface, and to a coefficient depending on the nature of the surrounding medium. (It may be well to observe here that Coulomb proved this only for air and for electricity at rest, and that Ohm in his investigations also only contemplated air as the possible surrounding medium, not knowing at this early period anything of covered wires and cables.) Ohm supposes the potential of the surrounding air to remain constant; that is, to be quite independent of the quantity of electricity diffused into it from the body. In fact, he takes the potential of the air as at all times = zero.
3. If two bodies of different substance are brought into contact, they acquire, from the moment of a contact, a constant difference of potentials.

   This difference of potentials has since been termed "Electromotive Force;" and when this difference is due to equal but opposite potentials, it always represents the electromotive force of any galvanic element.

By aid of these three laws the propagation of electricity in bodies of any form and nature can be mathematically treated of.

I. Development of the General Differential Equation.

Before proceeding it will be necessary to explain the term "conductivity."

If we call dq the quantity of electricity conveyed in the time dt between two contiguous molecules whose potentials are v and v', then the first law may be expressed thus:

$$dq \propto (v - v')\, dt$$

and, further, since it is admitted that the propagation of electricity is from molecule to molecule, it follows that, for a given difference of potentials between two points, the quantity of electricity transferred in a given time-interval will be inversely proportional to the number of molecules through which it is transferred, *i.e.*, to the distance dx between the two points, that is

$$dq \propto \frac{(v - v')\, dt}{dx}$$

and, again, it is clear, for the same reason, that, for a given time-interval and a given difference of potentials between two equipotential sections at right angles to the axis of a prismatic body, the quantity of electricity transferred will be proportional to the number of molecules in the sections, *i.e.*, to the sectional area a of the body, thus

$$dq \propto \frac{a\,(v - v')}{dx}\,dt$$

Therefore $$dq = \frac{k\,a\,(v - v')\,dt}{d\,x} \quad \ldots \quad \ldots \quad (p)$$

where k is a constant—depending on the nature of the body—which is called the "specific conductivity of the body." We shall now determine the meaning of the coefficient k.

We can select some particular substance, and take its "conductivity" as the standard of conductivity. In the case of this substance we have $k = 1$

$$\therefore\ dq' = \frac{a\,(v - v')\,dt}{dx} \quad \ldots \quad \ldots \quad (q)$$

Hence by (p) and (q) $$k = \frac{dq}{dq'} \quad \ldots \quad \ldots \quad \ldots \quad (r)$$

We can now give the following definition : "The specific conductivity of any substance is the number expressing the ratio of the quantity of electricity conveyed between two sections of given area at a given distance from each other in a body composed of that substance by a given electromotive force in a given time, to the quantity of electricity conveyed between two sections of the same area at the same distance from each other in a body composed of the standard substance by the same electromotive force in the same time."

If in equation (q) we put $a = v - v' = dt = dx = 1$, we have

$$dq' = 1$$

that is, the unit quantity is that conveyed by the unit electromotive force in unit time through unit length of unit area of the standard substance, and equation (r) becomes :

$$k = dq$$

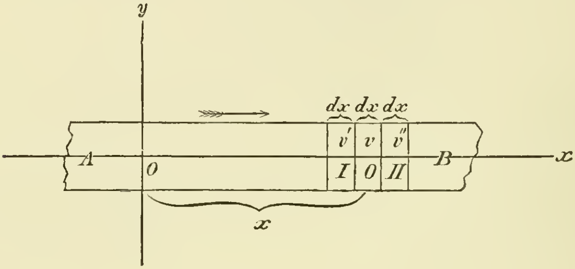
so that to measure the *specific conductivity* of any substance we have only to measure the *quantity* of electricity conveyed in unit time by unit electromotive force through a unit length of unit area of the substance.

Let A B represent a homogeneous prismatic body of sectional area a through which for some reason electricity flows.

Take $o\,x$, the axis of the body, as the axis of x, and $o\,y$, at right angles to $o\,x$, as the axis of y.

Now, considering most generally the distribution of electricity along the whole body A B, the potentials will not only be different at different cross sections at any the same time, but also will be different at any one section at different times. In other words the potential at any cross section will be a function of its *position* and of the *time* elapsed since the neutral state of the body was first disturbed. We shall, however, treat every cross section at right angles to the axis of the body as, at any given time, an element of an equipotential surface; *i.e.*, we shall suppose that the potential, while varying from time to time, is at any particular time the same at all points of such a cross section: this insures the propagation of electricity in the direction of the axis only—say in the direction indicated by the arrow.

At any point, distant x from o, by two cross sections cut out a small prismatic body (0) of length dx; and by two more sections cut out two more similar bodies, one on each side (1) and (2).



Let v be the potential of the small body (0) at the time t, v' that of (1), and v'' that of (2).

Thus $v' > v > v''$, as the electricity is supposed to move in the direction of the arrow.

Then the quantity of electricity dq' conveyed from (1) to (0) at the time t in the small interval dt is, k being the specific conductivity of the body

$$dq' = k\,a\,(v' - v)\,\frac{dt}{dx}$$

And similarly the quantity of electricity conveyed from (0) to (2) at the time t in the same time dt is (supposing k to be a constant for all points)

$$dq'' = k\,a\,(v - v'')\,\frac{dt}{dx}$$

The quantity of electricity, therefore, left in (0) at the time t is:

$$dq = dq' - dq'' = k\,a\,(v' + v'' - 2\,v)\,\frac{dt}{dx}$$

Now, whatever may be the distribution of electricity at the time t, it is clear that the potential v must be a finite and continuous function of x—so long at least as x does not attain the value belonging to the cross section in which the electromotive force is supposed to exist. Hence we can apply Taylor's Theorem, and express v' v'' in terms of v.

Thus
$$v' = v + \frac{dv}{dx}\, d\, x + \frac{d^2 v}{d\, x^2}\, \frac{(d\, x)^2}{2} + \ldots.$$

and
$$v'' = v - \frac{dv}{dx}\, d\, x + \frac{d^2 v}{d\, x^2}\, \frac{(d\, x)^3}{2} - \ldots.$$

$$\therefore \quad v' + v'' = 2\, v + \frac{d^2 v}{d\, x^2} (d\, x)^2$$

or
$$\frac{v' + v'' - 2\, v}{d\, x} = \frac{d^2 v}{d x^2}\, d\, x$$

Substituting, we have
$$dq = k\, a\, \frac{d^2 v}{d\, x^2}\, dx\, dt$$

expressing the quantity of electricity left in (0) at the time (t), and this quantity would remain in the small body if nothing were received by the surrounding medium. This loss, however, may be appreciable, and is given by the 2nd fundamental law as follows :—

$$\varphi\, s\, v\, d\, x\, d\, t$$

where φ is a coefficient depending on the nature of the surrounding medium, sdx the surface of the prismatic body in contact with the medium, and v the uniform potential of the surface at the time t.

Thus, considering the loss, we have
$$d\, q = k\, a\, \frac{d^2 v}{d\, x^2}\, d\, x\, d\, t - \varphi\, s\, v\, d\, x\, d\, t$$

representing the total quantity of electricity imparted at the time t during the interval dt to the small body (0).

But the charge communicated at the time t during the time dt to the small body (0) can also be calculated directly.

For, calling dv the increase of potential at (0) during the time dt, we have
$$d\, q = a\, dv\, dx$$
$$= a\, \frac{dv}{dt}\, dt\, dx$$

These two expressions for $d\, q$ must be equal, provided that always the same increase of potential represents the same increase of quantity.

If this is not so, the latter expression must be modified by a coefficient representing this quality of matter before the two expressions are equated to one another.

Let ψ be this constant.

Then we have

$$\therefore \qquad k\,a\,\frac{d^2 v}{d x^2}\,dx\,dt - \varphi\,s v\,dx\,dt = \psi\,a\,\frac{d v}{d t}\,dt\,dx$$

or

$$k\frac{d^2 v}{d x^2} - \frac{\varphi}{a} s v = \psi\frac{dv}{d t}$$

which is the general differential equation given by Ohm for the propagation of electricity in a prismatic body in the direction of its axis; and it is now only a mathematical problem to express v as a function of x and t. This, however, is not our purpose, as we only wish to deduce "Ohm's Law."

II. OHM'S LAW DEDUCED FROM THE GENERAL DIFFERENTIAL EQUATION.

The propagation of electricity is generally effected with such enormous rapidity, especially in the case of galvanic electricity in bodies of high conductivity, that already a moment after the first disturbance of the neutral condition, the distribution becomes sensibly constant with respect to time, that is, we have $\frac{dv}{dt} = o$; and consequently the general differential equation as given above becomes

$$k\frac{d^2 v}{d x^2} - \frac{\varphi}{a} s v = o$$

and, further, neglecting the loss of electricity into the surrounding medium, *i.e.*, supposing the quantity lost to be indefinitely small compared with the quantity passing in the direction of the axis, we have

$$\frac{d^2 v}{d x^2} = o$$

This differential equation represents the distribution of potentials along a prismatic body when there is no loss of electricity into the surrounding medium, and the potential at every point is constant with respect to time. This is the case when galvanic electricity is propagated along a good conductor (the *retardation* in cable excepted).

The above differential equation expresses the fact that every cross section of the body receives from the section immediately before it exactly the same quantity of electricity as it gives up to the one immediately after it.

The solution of
$$\frac{d^2 v}{d x^2} = o$$
is
$$v = m x + c$$
where m and c are constants.

To determine m we shall suppose the difference of the potentials at the two points x' x'' given, but not the absolute values of these potentials.

Then we have
$$\begin{aligned} v' - v'' &= e \\ v' &= m x' + c \\ v'' &= m x'' + c \\ \therefore \quad v' - v'' &= m(x' - x'') = e \end{aligned}$$

But $(x' - x'')$ is the distance between the two points, which we shall call l; thus we have
$$v = \pm \frac{e}{l} x + c$$

or let (e) contain the $\pm$ sign, we have
$$v = \frac{e}{l} x + c$$

The second constant c is generally indeterminate, and it expresses the power we have of altering the distribution of electricity by external influences.

For instance if we suppose the potential of a certain cross section at the distance b is kept at zero; then for this section we have
$$o = \frac{e b}{l} + c$$
$$\therefore \quad c = -\frac{e b}{l}$$

Hence
$$v = \frac{e}{l}(x - b)$$

and the distribution is fully determined.

Again suppose the potential at the point b is kept constant, say $= p$

Then
$$p = \frac{e}{l} b + c$$
$$\therefore \quad c = p - \frac{e}{l} b$$

Hence
$$v = \frac{e}{l}(x - b) + p$$

and the distribution is fully known.

We can, therefore, always determine the constant c, when, in addition to the finite difference of potentials (the cause which maintains the flow of electricity), the potential at *some* one point is given.

The next question is, how to find c when the potential at *no* point is known.

The answer is given by the following considerations. If the neutral condition of a body is disturbed by a cause existing in the body itself, both modes of electricity must exist in equal quantities, and, therefore, in this case, the two ends x', x'' of the prismatic body must have equal but opposite potentials, and the potential at the middle point must be zero. This case we always have when the body connects the two poles of a galvanic element.

Thus $$o = \frac{e}{l}\frac{l}{2} + c$$

$$\therefore \qquad c = -\frac{e}{2}$$

Hence $$v = \frac{e}{2}\frac{x - l}{l}$$

The quantity of electricity transferred between the equipotential surfaces (1) and (o) was expressed by

$$a\,k\,\frac{v' - v}{d\,x}\,dt$$

Putting $$v' - v = dv$$

we have $$a\,k\,\frac{dv}{dx}\,dt$$

and this quantity of electricity, moving at the time t towards (o) during the time dt, might appropriately be called the "electric current" in this section at the time t and during the time dt.

Or, if this current is constant with respect to time, we can consider the *quantity conveyed in the unit of time* and call it the *electric current* generally. This current would be expressed by

$$C = a\,k\,\frac{d\,v}{d\,x}$$

Now we have $$v = \frac{e}{l}x + c$$

$$\therefore \qquad \frac{dv}{dx} = \frac{e}{l}$$

$$\therefore \qquad C = a\,k\,\frac{e}{l}$$

$$= \frac{\frac{e}{l}}{a\,k}$$

$$= \frac{e}{r}$$

r being a quantity depending on the length, section, and nature of the prismatic body, which has been called the "electrical resistance." e, as before mentioned, is called the electromotive force.

Thus we have

$$\text{current} = \frac{\text{electromotive force}}{\text{resistance}} \text{ (Ohm's Law)}$$

If the body through which the electricity is propagated be not prismatic, Ohm's general law will still hold good; but that which we have called the electrical resistance will be different.

APPENDIX II.

KIRCHOFF'S COROLLARIES TO OHM'S LAW.

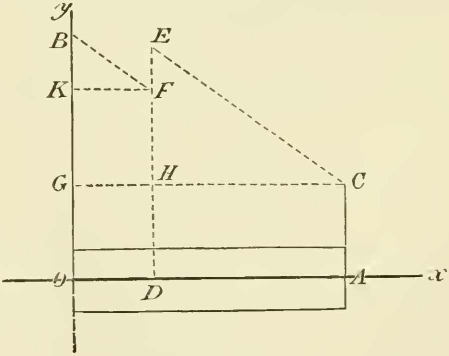
1. *The algebraical sum of all the currents that meet in a point is = zero.*

Reckoning all the currents going in one direction—either *to* or *from* the point—as positive, and all the currents going in the opposite direction as negative, it is obvious that, if no accumulation or loss of electricity occur at the point of meeting, the quantity of electricity brought to that point by the approaching currents in a given time must be equal to the quantity of electricity carried away from that point by the receding currents in the same time. Hence representing by C_1 all the approaching currents, and by C_2 all the receding currents, we have

$$C_1 - C_2 = o$$

If, however, the point at which the different branches meet form part of one coating of a condenser, then this law would not hold until after the condenser had approximately received its maximum charge.

2. *The algebraical sum of the products of all the currents which flow in any number of conductors forming a closed figure into the resistances of the conductors through which they respectively flow, is equal to the algebraical sum of all the electromotive forces in the conductors, provided we follow the figure round in one direction, and consider all the currents which flow, and all the electromotive forces which act, in one direction positive, and all the currents which flow, and all the electromotive forces which act, in the opposite direction negative.*



Let $O\,A$ be a homogeneous prismatic body.

Take $O\,x$, along the axis of the body, as the axis of x, and $O\,y$, at right angle to $O\,x$, as the axis of y.

Let v be the potential at O represented by $O\,B$, v' the potential at A, represented by $A\,C$, and let there be an electromotive force e at the point D, represented by $E\,F$.

Let R be the resistance between O and A, r' the resistance and e' the electromotive force, represented by $B\,K$, between O and D, and r'' the resistance and e'' the electromotive force, represented by $E\,H$, between D and A. Thus

$$R = r' + r''$$

Now

$$\begin{aligned} E\,H &= F\,H + E\,F \\ &= K\,G + E\,F \\ &= B\,G - B\,K + E\,F \end{aligned}$$

$$\therefore \quad e'' = v - v' - e' + e$$

$$\therefore \quad e'' + e' = v - v' + e$$

But

$$\frac{e'}{e''} = \frac{r'}{r''}$$

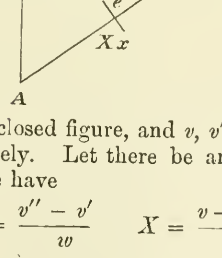
$$\therefore \quad e' = \frac{v - v' + e}{R}\,r'$$

and

$$e'' = \frac{v - v' + e}{R}\,r''$$

Hence, calling C the current, we have

$$\begin{aligned} C &= \frac{e'}{r'} = \frac{v - v' + e}{r' + r''} = \frac{e''}{r''} \\ &= \frac{v - v' + e}{R} \end{aligned}$$



Now let $A\ B\ C$ be any closed figure, and v, v' v'' the potentials at the points A, B, C respectively. Let there be an electromotive force e in the side $A\ B$. Then we have

$$G = \frac{v'' - v}{g} \qquad W = \frac{v'' - v'}{w} \qquad X = \frac{v - v' + e}{x} \text{ (as proved above).}$$

$$\therefore\ G\,g = v'' - v \quad W\,w = v'' - v' \quad X\,x = v - v' + e$$

$$\therefore \qquad G\,g + X\,x - W\,w = e$$

APPENDIX III.

BATTERY TESTING.

The methods that have been suggested for measuring the *resistance* and *electromotive force* of batteries, although exceedingly numerous, may all be divided into two classes, *viz.*:—"Differential" or "Compensation" methods, and "Deflection" methods.

The latter, although they do not generally give the same simple formulæ to express the unknown quantities, are, nevertheless, much more accurate than the former. It is well known that by opposing two batteries—as is invariably done in the compensation methods—the resistances, as well as the electromotive forces, of the batteries are very materially altered by virtue of polarisation, and, therefore, the very quantities which we set ourselves to measure are no longer constant, and no accuracy of results can be expected so long as the law of variation is unknown. The deflection methods, too, are not quite perfect, insomuch that a battery when short-circuited, *i.e.*, doing a maximum amount of work, cannot have the same electromotive force and resistance as when the circuit is completed through a high resistance—*i.e.*, when doing less work; and this for the same reason, *viz.*:—polarisation.

A most excellent method of comparing electromotive forces—perhaps only second to measurement by the electrometer—is undeniably the "condenser" method. One and the same condenser is successively charged by the two batteries whose electromotive forces are to be compared, and the discharges are measured by the throw of a galvanometer needle, being proportional to the sines of half the deflections, or, in the case of Thomson's Mirror Galvanometer, to the deflections themselves. The time of charging the condenser should be sufficiently long to approximately raise the potential of the condenser to a maximum. One minute will suffice.

It must, however, be left to each testing officer to measure the constants of his testing battery by any accurate method that he finds most convenient with the instruments he has.

In many testing offices, where a Tangent Galvanometer is used in the Wheatstone's Bridge, the following deflection method of measuring the *resistance* of the testing battery may be used. See Fig. 1.

Make $a = \infty$
$b = o$
$w = o$

and note the deflection a° which the battery gives through the thick coil of the galvanometer, the resistance of which is r.
Then we have

$$\tan a^\circ = \frac{E}{f + r}$$

Again, make $a = \infty$
$b = o$
$w =$ A resistance which must not be made so large as to reduce the deflection below a readable extent.

Then we have, b° being the deflection,

$$\tan b^\circ = \frac{E}{f + r + w}$$

Whence

$$f = \frac{\tan b^\circ}{\tan a^\circ - \tan b^\circ} w - r$$

To compare the *electromotive force* of the battery with that of the *standard cell* (e), the thin coil must be used, the resistance of which is R.

Make $a = \infty$
$b = o$
$w' =$ A resistance not too large to get a readable deflection with the standard cell.

Then we have, a° being the deflection,

$$\tan a^\circ = \frac{e}{c + R + w'}$$

c being the known resistance of the standard cell.

Again, make $a = \infty$
$b = o$
$w'' =$ A resistance which makes the deflection with the battery the same as that obtained with the standard cell.

Then we have

$$\tan a^\circ = \frac{E}{f + R + w''}$$

Whence

$$E = \frac{f + R + w''}{c + R + w'} e$$

Where a Differential Galvanometer is available, the following method of measuring the *resistance* of the testing battery may be adopted.

See Figure 4. Insert the plug p. Let a° be the deflection obtained with the resistance w' unplugged, which must not be so large as to reduce the deflection below a readable extent.

Then we have

$$a^\circ = \frac{m\,E}{f + w' + \frac{s\,g}{s+g}} \cdot \frac{s}{s+g}$$

where m is constant representing the deflection by the coil g with the unit of current.

Again, insert the plug q, join the two coils $g\,g'$ so that the current flows through them successively. And unplug more resistance until the deflection is reduced to what it was before. Let w'' be the total resistance now unplugged.

Calling b° the deflection which the first coil g now would give if acting alone, and b'° the deflection which the second coil g' would give if acting alone, we have

$$a^\circ = b^\circ + b'^\circ$$

Further, we have

$$b^\circ = \frac{m\,E}{f + w'' + \frac{s\,g}{s+g} + \frac{s'\,g'}{s'+g'}} \cdot \frac{s}{s+g}$$

$$b'^\circ = \frac{m'\,E}{f + w'' + \frac{s\,g}{s+g} + \frac{s'\,g'}{s'+g'}} \cdot \frac{s'}{s'+g'}$$

Hence substituting for a° b° b'° their values, we have

$$\frac{s}{s+g} \cdot \frac{m}{f + w' + \frac{s\,g}{s+g}} = \frac{1}{f + w'' + \frac{s\,g}{s+g} + \frac{s'\,g'}{s'+g'}} \left\{ \frac{m\,s}{s+g} + \frac{m'\,s'}{s'+g'} \right\}$$

Further, substituting $\frac{1}{n}$ for $\frac{s}{s+g} = \frac{1}{1+\frac{g}{s}}$

$$\frac{1}{n'} \quad \text{''} \quad \frac{s'}{s'+g'} = \frac{1}{1+\frac{g'}{s'}}$$

$$\frac{g}{n} \quad \text{''} \quad \frac{s\,g}{s+g}$$

$$\frac{g'}{n'} \quad \text{''} \quad \frac{s'\,g'}{s'+g'}$$

where n and n' are the multiplying power of the shunts, we have

$$\frac{\frac{m}{n}}{f + w' + \frac{g}{n}} = \frac{1}{f + w'' + \frac{g}{n} + \frac{g'}{n'}} \left(\frac{m}{n} + \frac{m'}{n'} \right)$$

Putting $\frac{m}{m'} = k$ – the constant of the differential arrangement,

we have
$$\frac{k}{nf + nw' + g} = \frac{\frac{k}{n} + \frac{1}{n'}}{f + w'' + \frac{g}{n} + \frac{g'}{n'}}$$

$$\therefore \quad f = \frac{k(nn'w'' + gn' + g'n) - (nw + g)(kn' + n)}{n^2}$$

which is the general formula for expressing the battery resistance, when *any* differential arrangement is used in taking the measurement; and which formula must become the particular one applicable in the case of our special Differential Galvanometer, if we substitute

$$k = 1$$
$$g' = g$$
$$n' = n$$

Then we have

$$f = w'' - 2w'$$

or, taking the first measurement with $w' = o$,

$$f = w''$$

which is the most simple case.

PART II.

ON LINE TESTING.

Having in the *first* Part explained the theory and use of the two arrangements most suitable for measuring resistances such as we have to deal with, we are now in a position to examine the problems which practically arise in line testing, and to this subject the *second* Part will be devoted.

How, by the aid of certain measurements, to determine the electrical condition of lines, to localise Faults, and to discover the relative merits of various modes of construction with respect to climatic influences, are the most important points which we shall have to discuss.

In *Appendices* we shall describe briefly the methods of testing insulators, short lengths of cable, telegraph earths, and anything else upon which it might appear necessary hereafter to write especially.

The testing of Telegraph Lines may be conveniently considered under two heads, viz. :—"Regular Testing" and "Fault Testing;" and these will be the subjects of the following two sections.

The "Regular Tests," having for their object the determination of the normal electrical condition of the lines, must be made as frequently as practicable, but never at such hours as to interfere seriously with traffic.

The electrical condition of any line, *i.e.*, its conduction, insulation, and state of natural electrification, will obviously depend on its mode of construction, and the meteorological character of the countries it traverses. The quantitative determination of the influence of either of these two causes by a series of tests, carefully executed and sufficiently numerous, cannot but lead to steady improvement in the construction of over-land lines—just in the same way as the rigorous tests of insulated wires have improved the manufacture of core for cables—and to many other results of scientific value.

The particulars of these tests should be recorded in such a manner as to show at a glance the condition of any given line. A sample "Test-sheet," filled in from actual tests made in India, is given at the end of Section I.

The "Regular Tests" will also furnish *data* necessary for the localisation of Faults.

"Fault Testing" has for its object the localisation of all defective points in a line, including not only those which actually interrupt or interfere with communication, but also those which may ultimately do so if neglected.

PRELIMINARY.

In Part I. formulæ were developed, both in the case of Wheatstone's Bridge and of the Differential Galvanometer, on the hypothesis of a current existing in the resistance to be measured, independent of the testing current. This is almost invariably the case with the resistances we have to measure in testing telegraph lines. Hence the utility of these formulæ.

I. *NATURAL CURRENTS.*

These currents, which are observed more or less in all lines, and which, if they attain a certain strength, interfere with working, are due to various causes:—

§ 1. *Polarisation of the Earth-plates.*—In this case the current is in the opposite direction to the sending current of that station which has most work, or, at all events, which has sent most recently. If two stations work with different battery power, the stronger will overcome the weaker, and, for equal times of working, the polarisation current in the line will be in the opposite direction to the working current of that station which has the stronger battery. In India, where positive working currents are invariably used, or copper to line, this polarisation current between the two earth-plates must always appear as a copper current flowing in a direction opposite to that of the working current of the station which has sent most recently, or which has the stronger battery.[1]

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[1] These polarisation currents have become much reduced in strength since the introduction of large-sized copper earth-plates, which are either sunk into suitable wells or in damp ground, and are connected with the signalling offices by good conducting and highly insulating

§ 2. *Galvanic Action between the Earth-plates.*—The direction of the current in this case will depend on the nature of the plates used, and of the soil in which they are placed. In all the Indian stations, as mentioned before, we have copper plates, sunk either in damp soil or in suitable wells; and thus, the same metal being used at both ends of the line, but slight galvanic action can ensue, and the direction of the current cannot be predicted. Experience goes to show that, under these conditions, the currents arising from this cause may be neglected in comparison with those produced by polarisation.

§ 3. *Earth Currents.*—These are caused by a difference of potentials between the two points of the earth with which the earth-plates are in contact. To measure these currents, and to determine their direction and the electromotive force producing them, is of the greatest scientific interest. The phenomenon of earth currents is generally, however, much obscured by the causes already mentioned—especially the polarisation of earth-plates—and by other causes which we shall hereafter speak of. All that we can do is to measure the total effect of all the causes acting, and only rarely are we able to attribute to each cause its proper effect. Still we are enabled to say, from many years' experience of testing the Indian lines, that real *earth currents* do permanently exist, although we have not been able to

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leading wires. Formerly iron wire coils and ropes were used, a metal and a form of earth-plate very objectionable; and no precaution being taken to insulate the leading wire, between earth and office, from the ground, the whole was necessarily highly favourable for the production of strong polarisation currents. In India the introduction of gas and water is not as yet as general as in Europe, and therefore the very convenient means of forming an *earth* by using the gas or water pipes are not generally available.

estimate the electromotive force, and to determine the law of change in direction in each particular case. To be in a position to do this, special observations would be necessary.

When two stations are situated at different altitudes, earth currents are generally observed in the lines connecting them—the direction of the currents being from the higher to the lower station. Earth currents attain their maximum strength when those "magnetic storms" occur which seem to accompany all great perturbations of the sun's surface, and which are generally marked by the appearance of vivid auroras. During such periods, as in the autumns of '48, '59, and '70, communication is rendered impossible, except in cases where the *earths* can be thrown off and a second wire used for the return circuit.[1] [2]

§ 4. *Atmospheric Electricity.*—In this case currents are generated either by the direct contact of the wire with electrified air, or by the inductive action of electrified clouds, moving, or changing their electrical condition, in the presence of the wire, or occasionally, by a discharge taking place between an electrified cloud and the wire. Such currents are either so extremely weak as to elude detection by ordinary instruments, or so violently strong as forbid any attempt at measurement, and being always exceedingly transient, are scarcely to be classed as an especial feature of telegraph lines.

§ 5. *Defective Insulation at a few points* in a line is a fruitful source of currents. At all such points polarisation is produced by the working currents, in a manner precisely similar to that of the earth-plates, by the same cause, already alluded to, and to a degree dependent on the resistance and the position of the Faults. These currents will be strongest in rainy weather, when the line is in contact with trees, when the insulators are covered with dew,—in fine, under those circumstances which diminish the resistance of the Faults, and promote electrolytic action.

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[1] The three above-mentioned causes would be active in the best insulated lines, including long submarine cables, and their effects could always be measured, and their magnitude calculated exactly by formulæ, provided they kept constant during the time of observation.

[2] On the 10th of November 1871, and 4th of February 1872, considerable natural currents were observed in the lines throughout India, and in the submarine cables terminating on its shores.

The stronger the working currents used, and the fewer the defective points, the stronger will be the polarisation currents.

If these currents become very strong, their direction may be reversed by sending for a short time a strong current with zinc to line; and, in such a case, this invariably indicates a single Fault in the line or Cable.

§ 6. *Thermo-Electric Currents* are generated by different points of the line wire having different temperatures at the same time. These currents will generally be exceedingly weak, and will be overpowered by the currents produced by the causes already mentioned. If we, for instance, imagine a line running from a cold station in the hills down to a station situated in the hot plains of India, and if we suppose that the temperature of the line wire increases continually from the colder station to the warmer, and that also the wire alters its molecular condition in the same sense from station to station, it is clear that such a line would represent a thermo-electric pile consisting of an innumerable number of thermo-couples, which, though perhaps varying in electromotive force, are nevertheless joined consecutively—adding their single effects—and the current produced might be appreciable. But these two conditions—namely, of the alteration of the temperature and the molecular condition in the same direction—are scarcely fulfilled with an extensive overland line; especially not the latter condition, since a telegraph wire is generally homogeneous throughout, and, consequently, any heterogeneity which may exist in a line will be rather accidental than otherwise. Hence the thermo-electromotive forces in a telegraph line, already weak in themselves, will generally neutralise one another in part, and the resultant current must invariably be small.

§ 7. *Charges and Discharges.*—In testing long (over 200 miles) and well-insulated overland lines, the effect of the *charge* and *discharge* of the line will be felt in the same manner as in cable testing. To obtain reliable results that can be compared *inter se*, the readings should always be taken after the testing current has been on for a fixed interval of time—long enough to eliminate the effects of charge; and between the tests made with positive and negative currents, the line should be put to earth for at least double this fixed time to eliminate the effects of discharge. It must be left to the observer to vary the lengths of these intervals as the state of the line may demand. However, testing for fixed intervals of time is only necessary when the greatest accuracy is desired, and is only consistent so long as the error involved by its omission would exceed in magnitude the combined errors due to many other active causes, whose nature does not permit of their elimination, nor even of their control, in practical electrical observations.

§ 8. *Volta-Induction.*—Two wires running sufficiently close to one another must always act upon each other inductively when a current begins or ceases in one of them.

Namely, a "make contact" of the primary current in the one wire will cause an induction current of opposite direction in the other wire; while a "break contact" of the primary current in the one wire will cause an induction current of the same direction as the primary current in the other wire.

These Volta-Induction currents cannot be mistaken for currents due to contact, because the latter are constant while the induction currents are necessarily momentary. However, both may sometimes add their effects, and then the induction is more apparent. When therefore signalling through the one wire, signals with opposite signs must invariably pass through the other wire. These induction signals are, however, generally not strong enough to affect our receiving instruments, especially when the lines running on the same posts are comparatively short and more than two in number.

It is only in cases of very long double lines that Volta-Induction has been observed to interfere with traffic. This is, for instance, the case on the Madras-Bombay wires, which run for 797 miles parallel on the same posts along the railway, and are worked direct.

There are at present no other means of overcoming this difficulty than to break up one of the two double lines and work it in translation through one or more intermediate stations; or, if more than two wires run together on the same posts, to select those wires for through traffic which are furthest away from each other.

In testing, however, especially when taking the insulation of a line, these Volta-Induction currents may often be exceedingly inconvenient, even on lines where they are not felt by the telegraph instruments. The testing officer in such a case should, therefore, for a moment, stop the working on that line which influences the line under test, to be able to get reliable results.

II. *MEASUREMENT OF NATURAL CURRENTS.*

The formulæ, already referred to, given in Part I., for finding the *true* value of the unknown resistance from the two *measured* values, were developed on the supposition that the difference between the values was due to the fact of a natural current of constant strength and direction existing in the resistance under measurement. Hence they are only applicable so long as this condition is fulfilled.

It will be always necessary, therefore, to ascertain whether the natural current remains constant or not. For this purpose, we must, *before* and *after* each measurement, put the line to earth through the galvanometer and note the deflection.

When testing with a bridge, this is best done by letting the current flow through g and w,[1] as we thus have it in our power to modify the effect of the current on the galvanometer, both by unplugging resistance in w, and by using the circuit $a + b$ as a shunt. It is clear that, in order that the two deflections, before and after test, may be comparable, either the same values must be given to $a + b$ and w in both cases, or any difference of value must be taken into account. To use the same values is more convenient.

III. *THE SELECTION OF FORMULÆ.*

§ 1. *The difference of values is due to a* constant *natural current.*—Having ascertained that the natural line current has remained constant while the measurements were made, we know that the formulæ given in Part I. (Para. VI. of Sec. I., and Para. VI. of Sec. II.) are applicable.

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[1] Fig. 1, Part I.

Should the *difference* between w' and w''[1] *exceed* 10 *per cent.*, formula (2) or (4) or (6) of Section I., or (2′) or (4′) or (6′) or (8′) of Section II., according to the circumstances of the case, must be used to find the *true* value of the resistance under measurement; and formula (3) or (5) or (7) of Section I., or (3′) or (5′) or (7′) or (9′) of Section II., to find the electromotive force producing the natural current. If, however, the difference falls short of 10 per cent., it will be unnecessary, unless extreme accuracy is desired, to have recourse to these formulæ, and the simple arithmetic mean may be taken as in formula (8).

§ 2. *The difference of values is due to a* variable *natural current.*—Should the natural line current be found to have varied considerably during the time of measurement, the arithmetic mean of the two *measured* values must be taken—formula (8)—as giving the best approximation to the *true* value. The electromotive force producing the natural current cannot in this case be calculated.

§ 3. *The difference of values is due to* chemical action.—It will occasionally be found, especially in measuring the insulation resistance, that, although there is no natural current in the line, still two different resistances have to be unplugged to obtain balance with reversed test currents. This is generally attributed to the electrolytic action of the testing current. When zinc is to line, all the points at which the current escapes to earth are cleaned, and consequently the resistance is diminished; on the other hand, when copper is to line, the points of leakage are oxidised, and the resistance increased. Clearly this action can only occur on a well-insulated line having a *few* defective points; for were the leakage distributed over a great number of points, the current escaping at any particular point would be too feeble to produce any chemical action.

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[1] If w'' is greater than w', the natural positive current flows from the testing station; and if w'' is less than w', it flows towards the testing station. In the first case e will be positive, in the second case negative.

In this case, also, the arithmetic mean of the two *measured* resistances must be taken—formula (8)—as giving the best approximation to the *true* resistance.

Remark.—On all the lines in India positive signalling currents (copper to line) are used in order to have the greatest possible insulation of each line under all circumstances. Now, when measuring the insulation of a line with a positive test current, it is evident that the value obtained must give the insulation much too high, *i.e.*, higher than the line actually has when signals pass through it; because the signalling currents can only have a comparatively small oxidising effect on the line, since only a very small part can escape to earth in the different points of the line, while a positive testing current, the further end of the line being insulated, must all escape to earth at the defective points of the line. Again, when measuring the insulation of a line with a negative testing current, we get a value which gives the insulation of the line much too low, because negative signalling currents are never used. In the absence of any known law, which would give us how much too high the insulation of the line is obtained with a positive testing current, and how much too low with a negative testing current, we can do nothing better than to take the arithmetic mean of the measured values, as representing the insulation the line probably has when signals are passing through it. Of this mean it may, however, be said, that it must be always somewhat too low, for the very reason that negative signalling currents are never used, and, therefore, the arithmetic mean again of the *first mean* and the *positive measured value*, would represent a value most probably approximating to the one which the line actually has when signals pass, and which alone is of practical interest and consequence to be known.

SECTION I.

REGULAR TESTING.

"Regular Tests" are divided into "Conduction Tests" and "Insulation Tests." The former are taken to ascertain the resistance offered to the passage of the current by the line wire; the latter to ascertain the resistance, against the escape of the current from the wire to the earth, which is offered by the insulating medium.

I. *Measurements with a Single Line.*—On a single line the following three measurements can be made :—

1. The wire being put *to earth through the relay* at the distant station, we can measure the resistance of the working circuit. This may be appropriately called the "CIRCUIT" test, and the resistance measured will always be denoted by W.
2. The wire being put *direct to earth* at the distant station, *i.e.*, the relay being short-circuited, we can measure the resistance of the wire alone. This may be called the "CONDUCTION" test, and the resistance measured will be denoted by w.
3. The wire being *insulated* at the distant station, we can measure the insulation of the line. This may be called the "INSULATION" test, and the resistance measured will be denoted by I.

II. *Circuit Test.*—From the "circuit" test we ascertain the resistance of the line wire together with the receiving instrument at the distant station. This test, however, is taken not so much for this purpose, although of course it is useful as affording a check on the "conduction" test, as for the purpose of obtaining a third equation, by the help of which we are enabled to solve the equations obtained by the other two tests.

The primary object of testing is, as above stated, to discover the "conduction" and the "insulation" of the line. The importance of the "circuit" test, therefore, although none the less great, as will be presently seen, from the significance of the criterion afforded by the value of the "measured" relay, is subsidiary and indirect.

III. *Conduction Test.*—From the "conduction" test we ascertain the *absolute* conduction resistance, or that offered by the whole line. To find x the resistance *per mile* of a line composed of wire of uniform gauge, we have only to divide by the number of miles n. Thus,

$$x = \frac{w}{n} \quad \ldots \quad \ldots \quad \ldots \quad (13$$

When a line consists of wires of various gauges, by dividing by the number of miles we only obtain the *average* resistance *per mile.* This is insufficient. To have a correct knowledge of the state of a line throughout its whole length, the resistance *per mile of each gauge of wire* employed must be known, and this can be easily calculated if the lengths of the different gauges be given.

Thus, supposing a line to consist of two gauges of wire of which the diameters are d_1 and d_2, and the lengths l_1 and l_2 respectively, and calling the resistances per mile x_1 and x_2, we have

$$x_1 = \frac{d_2^2}{l_1 d_2^2 + l_2 d_1^2} w$$

$$x_2 = \frac{d_1^2}{l_1 d_2^2 + l_2 d_1^2} w$$

provided the two wires of different gauges have the same specific resistance.

And, generally, if we have n gauges of diameters $d_1\ d_2\ d_3 \ldots$ and of lengths $l_1\ l_2\ l_3 \ldots$ respectively; then the per mile resistance of any particular gauge of diameter d_a and of length l_a is

$$x_a = \frac{w}{d_a^2 \Sigma_1^n \frac{l}{d^2}} \quad \ldots \quad (14)$$

provided the wires of different gauges have the same specific resistance.

The quantity $\Sigma_1^n \frac{l}{d^2}$ is a number which remains constant for any line so long as the wire composing that line is not altered; and, therefore, it will be only necessary to calculate its value once for all.

Again, the quantity $d_a^2 \Sigma_1^n \frac{l}{d^2}$ need be only once calculated for each gauge of wire in the line. Supplying the various values of d corresponding to the several gauges of wire and evaluating, we obtain a set of divisors by the help of which we are at once able to determine from the known resistance of the whole line the resistance per mile of each gauge composing the line.

It may be well to remark here, that were the ratios of the resistances of the various gauges of wire known from accurate experiment, it would be incomparably better to use such known ratios instead of assuming the resistances to be in the inverse ratios of the squares of the diameters as above.

For, $$w = \psi \left\{ \frac{l_1}{d_1^2} + \frac{l_2}{d_2^2} + \cdots\cdots \frac{l_a}{d_a^2} + \cdots\cdots + \frac{l_{n-1}}{d_{n-1}^2} + \frac{l_n}{d_n^2} \right\}$$

$$= \psi \Sigma_1^n \frac{l}{d^2}$$

where ψ is the specific resistance.

If, now, x_a is the resistance per mile of the wire of diameter d_a, we have

$$x_a \, l_a = \psi \frac{l_a}{d_a^2}$$

$$\therefore \qquad \psi = x_a \, d_a^2$$

Hence,
$$w = x_a \, d_a^2 \, \Sigma_1^n \frac{l}{d}$$

$$\therefore \qquad x_a = \frac{w}{d_a^2 \, \Sigma_1^n \frac{l}{d^2}}$$

Say, for instance, that a certain line contains three different gauges, viz., 100 miles of No. 1, 50 miles of No. 5½, and 10 miles of No. 8.

In this case
$$\left.\begin{array}{l} l_1 = 100 \\ l_2 = 50 \\ l_3 = 10 \end{array}\right\} \text{ and } \left\{\begin{array}{l} d_1 = 0{\cdot}30 \\ d_2 = 0{\cdot}21 \\ d_3 = 0{\cdot}17 \end{array}\right.$$

Therefore

$$\Sigma_1^3 \frac{l}{d^2} = \frac{100}{(0{\cdot}30)^2} + \frac{50}{(0{\cdot}21)^2} + \frac{10}{(0{\cdot}17)^2} = 2590{\cdot}9$$

and, for this line, the formula becomes $x_a = \frac{w}{d_a^2 \times 2590{\cdot}9}$ and the set of divisors would be 233·18, 114·26, and 74·88—for the No. 1, No. 5½, and No. 8 wires respectively.

IV. *Insulation of a Line.*—If a line were perfectly insulated, the "insulation" resistance would be infinite; but, as all insulating materials conduct more or less, and lines are further subject to meteorological influences, which tend to diminish or destroy insulation, the range of the testing apparatus described in Part I., the highest limit of which is 1,000,000 units, will in most cases prove sufficiently great.

From the "insulation" test we ascertain the *absolute* insulation resistance of the line, or that opposed to the escape of the current from the wire to the earth along the whole length of the line.

To find y the insulation resistance *per mile* we must multiply by the number of miles, as obviously the longer the line the smaller will be the absolute insulation. Thus,

$$y = n\,I \qquad \ldots \qquad \ldots \qquad (15)$$

V. *Examples.*—Suppose the tests of a line 300 miles long, composed throughout of No. $5\frac{1}{2}$ wire, give the *absolute* conduction resistance 2925 ohms, and the *absolute* insulation resistance 40,000 ohms; then

$$x = \frac{2925}{300} = 9{\cdot}75 \text{ ohms} = \text{conduction resistance } \textit{per mile.}$$

$$y = 40{,}000 \times 300 = 12 \text{ megohms} = \text{insulation resistance } \textit{per mile.}$$

Again, suppose the tests of a line 250 miles long, consisting of 175 miles of No. $5\frac{1}{2}$ wire and 75 miles of No. 1, give the *absolute* conduction resistance 2070 ohms, and the *absolute* insulation resistance 30,000 ohms; then for the No. $5\frac{1}{2}$,

$$x_1 = \frac{(0{\cdot}3)^2 \times 2070}{175 \times (0{\cdot}3)^2 + 75 \times (0{\cdot}21)^2} = 9{\cdot}77 \text{ ohms } \textit{per mile;}$$

for the No. 1,

$$x_2 = \frac{(0{\cdot}21^2 \times 2070}{175 \times (0{\cdot}3)^2 + 75 \times (0{\cdot}21)^2} = 4{\cdot}79 \text{ ohms } \textit{per mile;}$$

and $y = 30{,}000 \times 250 = 7{\cdot}5$ megohms *per mile.*

VI. *Definitions.*—Before proceeding further, we must introduce the definitions of a few terms which will be of constant recurrence hereafter.

Def. i. The "CALCULATED" CIRCUIT RESISTANCE of any line is the theoretical resistance found by calculation, the temperature, the length, diameter and specific resistance of the wire composing the line, and the resistance of the relay at the distant station, being given.

Def. ii. The "REAL" or "CORRECTED" CIRCUIT RESISTANCE of any line, is the resistance that *would* be found from the "circuit" test, *if* the line were perfectly insulated from the ground, that is *if* there were no leakage whatsoever.

N.B.—Clearly, if the line is in a perfect state, the "corrected" and "calculated" circuit resistances ought to agree within the limits of observation errors.

Def. iii. The "MEASURED" CIRCUIT RESISTANCE of any line is that *actually* found from the "circuit" test. It is that which we have denoted by W.

N.B.—The "measured" circuit resistance must be always smaller than the "real;" for, as no line is ever perfectly insulated, we really measure the resistance of a multiple arc.

Def. iv. The "CALCULATED" CONDUCTION RESISTANCE of any line is the theoretical resistance found by calculation, the temperature and the length, diameter, and specific resistance of the wire composing the line being given.

Def. v. The "REAL" or "CORRECTED" CONDUCTION RESISTANCE of any line is the resistance that *would* be found from the "conduction" test, *if* the line were perfectly insulated from the ground; that is, *if* there were no leakage whatsoever. We shall denote it by L.

N.B.—Clearly, if the line is in a perfect state, the "corrected" and the "calculated" conduction resistances ought to agree within the limits of observation errors.

Def. vi. The "MEASURED" CONDUCTION RESISTANCE is that actually found from the "conduction" test. It is that which we have denoted by w.

N.B.—The "measured" conduction resistance must be always smaller than the "real;" for, as no line is ever perfectly insulated, we really measure the resistance of a multiple arc.

Def. vii. The "CALCULATED" INSULATION RESISTANCE of any line is the theoretical resistance found by calculation, the resistance per insulator and the number of insulators per mile being given.

Def. viii. The "REAL" or "CORRECTED" INSULATION RESISTANCE of any line is the resistance that *would* be found from the "insulation" test, *if* the conductor had no resistance or a resistance indefinitely small compared with the insulation resistance. We shall denote it by i.

N.B.—Clearly, for a given meteorological condition, the "corrected" and the "calculated" insulation resistances ought to agree.

Def. ix. The "MEASURED" INSULATION RESISTANCE of any line is that actually found from the "insulation" test. It is that which we have denoted by I.

N.B.—The "measured" insulation resistance must be always larger than the "real," for, in the case of long land-lines at least, the conduction resistance generally cannot be neglected against the insulation resistance.

Def. x. The "RESULTANT FAULT" of any line is that Fault which, if applied alone to the line at the proper point, would produce the same effects with respect to the sent and received currents as all the actually existing Faults do.

N.B.—The "resultant fault" has a determinate position and resistance. The "corrected" insulation gives the resistance of the "resultant fault."[1]

Def. xi. The "MEASURED" RELAY RESISTANCE is the resistance $(W - w)$, the difference between the "measured" circuit resistance and the "measured" conduction resistance.

VII. *General Expressions for the three Tests.*

Now, let L = the "real" conduction resistance of a given line.

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[1] See Appendix I. of this Section.

Now, let $l =$ the "real" conduction resistance of the line from the testing station to the Resultant Fault.
" $l' =$ the "real" conduction resistance of the line from the Resultant Fault to the distant station.
so that $L = l + l'$.

And let $i =$ the "real" insulation resistance.
" $r =$ the known resistance of the relay at the distant station.
" $k = \frac{l}{l'}$

Then, making the three tests, namely the "circuit" test, the "conduction" test, and the "insulation" test, we have the following three diagrams, representing the state of the line during the three tests :—

Fig. 5.

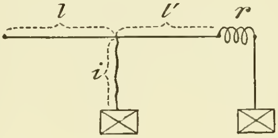


Fig. 6.

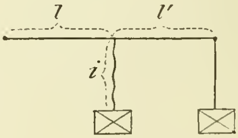
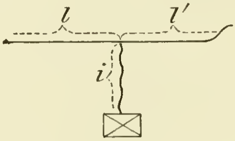


Fig. 7.



Hence, from Figs. I., II., III., by the known laws of derived circuits, we have

$$W = l + \frac{i\,(l' + r)}{i + l' + r} \quad \ldots \quad \ldots \quad (a)$$

$$w = l + \frac{i\,l'}{i + l'} \quad \ldots \quad \ldots \quad (b)$$

$$I = l + i \quad \ldots \quad \ldots \quad \ldots \quad (c)$$

VIII. *Special Expressions for the three tests.*—If now the insulation resistance be indefinitely large, compared with the resistance of the conductor, as is the case with perfect cables and very short well-insulated overland lines, we have

$$W = l + l' + r = L + r$$
$$w = l + l' = L$$
$$I = i$$

and $$W - w = r$$

that is to say, in this case the "measured" values are identical with the "real."

However, in the case of long overland lines, and of short lines in bad weather, the insulation resistance is not indefinitely large compared with that of the conductor, and, therefore, we shall always have

$$\left.\begin{array}{r} W < L + r \\ w < L \\ I > i \\ W - w < r \end{array}\right\}^{1}$$

The nearer the "measured" approximate to the "real" values, the better the line; and the greater the difference between them, the worse the line; and a line is totally interrupted so soon as $W - w = o$, as then obviously the distant relay can receive no current whatsoever. The best practical criterion, and that which the testing officer should first look to, is the value of $(W - w)$. If this difference closely approximates to the known resistance of the relay at the distant station, he may be satisfied with the "measured" resistances, as they will be very nearly equal to the "real," and he also knows at once that the line is perfect for all practical purposes.

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[1] It is useful to remember that these inequalities must always hold, and that the converse are impossible.

IX. *To obtain the real from the measured values.*—On the long lines of India, and especially during the monsoon, $(W - w)$ will always be found to be smaller than r, the known relay resistance ; and, therefore, the *necessary correction* must be applied to the "measured" values, in order to obtain the "real" values, before any conclusions can be based on them.

The form of the correction is supplied by equations (b) and (c). Solving these equations for i and L, we have, remembering $l = k\,l'$,

$$i = \frac{(I - w)(k - 1) + \sqrt{[\{(I - w)(k - 1)\}^2 + 4\,k\,I\,(I - w)]}}{2\,k}$$

$$L = (k+1)\frac{I(k+1) + w(k-1) - \sqrt{[\{(I-w)(k-1)\}^2 + 4kI(I-w)]}}{2\,k^2}$$

Hence, if k were known in each case, the "real" conduction and insulation resistances could be found by means of the above two equations. But as k is *not* known in those cases in which we require to use these general formulæ, the equations must be put into another form. This is obtained from the following considerations :—

Referring to the fundamental equations (a), (b), and (c), we observe that (a) only differs from (b) by involving the constant quantity r; and that, therefore, by using the equation (a), obtained from the "circuit" test, we are able to obtain solutions for i and L without introducing the unknown ratio k.

Thus $$i = \sqrt{\frac{(I - W)\,(I - w)\,r}{W - w}} \quad \ldots \quad \ldots \quad (16)$$

$$L = I + \frac{(I - W)\,r}{W - w} - 2\sqrt{\frac{(I - W)\,(I - w)\,r}{W - w}} \quad (17)$$

also $$l = I - \sqrt{\frac{(I - W)\,(I - w)\,r}{W - w}} \quad \ldots \quad \ldots \quad (18)$$

It will be seen that the third of these equations gives the distance of the Resultant Fault from the testing station.

X. *Resultant Fault at centre of conduction.*—There is, however, one very important case in which k is known. If, namely, a line consists of uniform gauge, and has also a uniform insulation throughout (which is the case with all well-constructed lines not subject at any point to extraordinary influences), or more general if the faults which cause the total leakage on any line (of uniform gauge or not) are situated symmetrically with respect to the centre of conduction resistance,[1] then the Resultant Fault will be *at the centre of conduction resistance,* that is $k = 1$, or $l' = l$.

Putting, then, $k = 1$ in Para. IX. we have

$$i = \sqrt{I\,(I - w)} \qquad \ldots \qquad (19)$$

$$L = 2\{I - \sqrt{I\,(I - w)}\} \qquad \ldots \qquad (20)$$

It must be clearly borne in mind that these formulæ are developed on the supposition of the Resultant Fault being at the centre of conduction resistance, and that they can only be used when this condition is fulfilled.

XI. *To find whether the Resultant Fault is at the centre of conduction or not.*—How to ascertain, now, whether the necessary condition is fulfilled, that is whether the Resultant Fault is at the centre of conduction Resistance or not, is the next question.

Developing r from equations (a), (b), and (c), we have

$$r = \frac{i\,[k\{i - (I - W)\} + (I - W)] - I\,(I - W)}{k\,(I - W)}$$

---

[1] We use the expression "Centre of Conduction Resistance" and not "Middle of the Line," as these two points will not necessarily be coincident when the line consists of various gauges of wire, which is frequently the case.

And putting $l' = l$, that is supposing the Resultant Fault to be at the centre of conduction Resistance,

$$r = \frac{I\,(W - w)}{I - W} \qquad \ldots \qquad \ldots \qquad (21)$$

Here, then, we have the required criterion. Whenever this equation (21) is true,[1] the Resultant Fault is at the centre of conduction resistance, and formulæ (19) and (20) may be used; but whenever equation (21) is not true, formulæ (19) and (20) *must not be used.*

XII. *Procedure.*—We can now lay down a definite course of procedure for the testing officer.

1. Make the three tests, viz.: "Circuit," "Conduction," and "Insulation."
2. Then there are three cases possible, viz.:—
   - i. $W - w = r$ *approximately.*[1] This is the simplest case, and can only occur, as has been already stated, when the ratio of the insulation resistance to the conduction resistance is very great. No CORRECTONS ARE NECESSARY, as the "measured" resistances will be very nearly equal to the "real." If $W - w$ not $= r$, then
   - ii. $\frac{I\,(W - w)}{I - W} = r$ *approximately.*[1] **This is the next simplest and the most general case, and is that in which the Resultant Fault is at the centre of conduction resistance; as before stated, it is the case with a good line of uniform gauge, not subjected at any point to extraordinary influences.**

     CORRECT THE MEASURED VALUES BY FORMULÆ (19) AND (20). If $\frac{I\,(W - w)}{I - W}$ not $= r$, then

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[1] In practice, say within 10 per cent.

iii. CORRECT THE "MEASURED" VALUES BY FORMULÆ (16) AND (17), which are perfectly general, always true, and applicable in all cases.

3. Having thus, by the formulæ applicable in the particular case, found the "real" *absolute* conduction and insulation resistances, next find the "real" conduction and insulation resistances *per mile.*

4. If there is a natural current in the line, calculate the magnitude of the electromotive force producing it by the proper formulæ.[1]

5. In the third case, *i.e.*, when l' not $= l$, the position of the Resultant Fault can be calculated by formula (18).

The electrical condition of the line will thus be completely determined, and it will only remain for the testing officer to carefully record his results, come to right conclusions, and give the required orders.

XIII. *Displacement of the Resultant Fault.*—If it is found that the equation $r = \frac{I(W - w)}{I - w}$ is not approximately fulfilled, the value of r obtained by it gives at once the direction of the displacement of the Resultant Fault with respect to the centre of conduction; namely, if r is *greater* than the known resistance of the relay at the distant station, the Resultant Fault is *further* away from the testing office than the centre of conduction; and if r is *smaller* than the known resistance of the relay at the distant station, the Resultant Fault is *nearer* towards the testing station than the centre of conduction. Now, in case of a line consisting throughout of uniform gauge, the displacement of the Resultant Fault proves at once that the line *cannot* be uniformly insulated throughout, and therefore, in such a case, the testing officer should endeavour without delay to discover the probable cause, as the displacement may simply arise from a remediable fault on the line. Sometimes, however, such a displacement may be due to unavoidable climatic influences, notwithstanding that the line is equally well constructed throughout. This is the case with the lines from Calcutta to Allahabad, where, owing to the notorious dampness of the climate of Lower Bengal, the Resultant Fault is thrown much nearer to Calcutta than to Allahabad. In case of a line consisting of different gauges, the order and lengths of which are known, it is not so easy to draw the conclusion, because the observed displacement may be right, *i.e.*, according to the different gauges used, notwithstanding the line being uniformly insulated throughout. However, under the supposition of a uniform insulation throughout, it will be always possible to calculate the position of the Resultant Fault, and with this the displacement as actually found should agree approximately; if not, the insulation could not have been uniformly distributed over the whole length of line, and it is then again the duty of the testing officer to discover if such an unequal insulation is due to unavoidable climatic circumstances, &c., or to imperfect insulators or any other remediable fault.

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[1] *See* Part I.; Sec. I., Para. VI.; Sec. II., Para. VI.; and Part II., Preliminary, Para. III.

XIV. *Position and Resistance of Resultant Fault.*— The position of the Resultant Fault and its resistance can always be calculated by the following two formulæ:—

$$l = \frac{\Sigma\left(\frac{r}{y}\right)}{\Sigma\left(\frac{1}{y}\right)} \quad \ldots \quad \ldots \quad \ldots \quad (22^1)$$

$$z = \frac{1}{\Sigma\left(\frac{1}{y}\right)} \quad \ldots \quad \ldots \quad \ldots \quad (23^1)$$

where y is the resistance of any real fault, the distance of which from the *one* end of the line is r (measured in resistances). Then l is the distance of the resultant fault (measured also in resistances) from the *same* end of the line.

It will be good to give a few examples to show the application of these two formulæ.

1*st Example.*—A line consists of three different gauges of wire, in the following order from the testing station towards the out-station :—

20 miles No. 9½ wire.
200 " " 5½ "
280 " " 1 "

Further, we will suppose the insulation to be uniform throughout, namely, J megohms per mile.

Therefore in this case we have to deal with three real faults, the positions and resistances of which are known ; namely, we have the following table :—

No. of Real Fault.	y	r
1*st.*	$\frac{J}{20}$	$10g'$
2*nd.*	$\frac{J}{200}$	$20g' + 100g''$
3*rd.*	$\frac{J}{280}$	$20g' + 200g'' + 140g'''$

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[1] See Appendix I. of this Section.

where g', g'', g''' are the resistances per mile of the No. 9½, No. 5½, and No. 1 wire respectively.

Thus by formula 22 we have

$$l = \frac{98 g' + 760\, g'' + 392\, g'''}{5}$$

or substituting

$$\begin{aligned} g' &= 20 \\ g'' &= 10 \\ g''' &= \ \,5 \end{aligned}$$

we have $l = 2304$ units or 210·4 miles, is the distance of the Resultant Fault from the testing station.

While the centre of conduction is at 1900 units or 170 miles from the testing station.

Or, generally, we have

In a line uniformly insulated throughout, but consisting of gauges which decrease in resistance permanently from station A towards station B, the Resultant Fault is necessarily nearer station A than station B.

The resistance of the Resultant Fault for formula 23 would be $z = \frac{J}{500}$, which is right obviously.

2*nd Example.*—A line consists of uniform gauge throughout, while the insulation per mile is not uniform, but is distributed as follows from the testing station towards the out-station :—

20 miles have an insulation per mile = J′ megohms.
200 ,, ,, ,, = J″ ,,
280 ,, ,, ,, = J‴ ,,

Therefore in this case we have to deal again with three real faults, the resistances and positions of which are known ; namely, we have the following table :—

No. of Real Fault.	y	r
1*st.*	$\frac{J'}{20}$	$10\,g$
2*nd.*	$\frac{J''}{200}$	$120\,g$
3*rd.*	$\frac{J'''}{280}$	$360\,g$

g being the resistance per mile of the uniform gauge.

Thus by formula 22 we have :—

$$l = \frac{\frac{10}{J'} + \frac{1200}{J''} + \frac{5040}{J'''}}{\frac{1}{J'} + \frac{10}{J''} + \frac{14}{J'''}}$$

and substituting $J' = 10$

$J'' = 5$

$J'' = 1$

we have $l = 328{\cdot}01\,g$, or the Resultant Fault is 328·01 miles distant from the testing station, while the centre of conduction is at 250 miles.

By formula 23 we have $z = 0{\cdot}0034$ (megohms), which gives an average insulation resistance per mile of 1·7 megohms.

In a line of uniform gauge, but with a permanent decreasing insulation per mile from station A towards station B, the Resultant Fault is necessarily nearer station B than station A.

These two examples will suffice, but the student may find it useful to add some more applications by supposing, for instance, different gauges and different insulation at the same time, &c. &c.

XV. *Sign of Error.*—In para. XIII. it was stated that the value of the corrected relay by formula 21 shows at once the displacement of the Resultant Fault with respect to the centre of conduction.

Namely, if the corrected relay is *larger* than the real relay, the Resultant Fault is *further* away from the testing station than the centre of conduction; and if the corrected relay is *smaller* than the real relay, the Resultant Fault is *nearer* to the testing station than the centre of conduction.

At the same time it may be useful to remember that the same is the case with the other corrected values as obtained by formulæ 19 and 20, when the position of the Resultant Fault does not coincide with the centre of conduction.

Generally we have, namely :—

Formulæ 19, 20, *and* 21 *give invariably values too large if the Resultant Fault is further away from the testing station than the centre of conduction, and they give invariably values too small if the Resultant Fault is nearer to the testing station than the centre of conduction.*

If the tester bears this in mind he will be able to decide at once *the sign of error* which has been made by using the more simple but inaccurate formulæ for correcting the measured values instead of using the true ones.[1]

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[1] This can be proved as follows :—

We will call n the displacement (in resistances) of the Resultant Fault with respect to the centre of conduction, and put

$$l = l' + n$$

XVI. *Variation of the Line during Test.*—It is obvious that the three fundamental equations a, b, and c can be correctly fulfilled only if i, l, and l' have remained *constant* during the time the three tests, *viz.*, "*Circuit*," "*Conduction*," and "*Insulation*," were executed.

This is, however, a supposition which is never fulfilled in practical line-testing, and thus the unknown quantities, i, l, and L, as calculated from the measured values, must always contain errors quite independent of observation errors, and due only to this unavoidable changing condition of the line under measurement.

---

where l is the distance of the Resultant Fault (expressed in resistance) from the testing station, and l' that from the other station.

Further, by the fundamental equation (c) we have

$$l = I - i$$

$$\therefore \quad l' = I - i - n$$

and these two values substituted in the fundamental equation (b) we get at once

$$i = \sqrt{(I - n)(I - w)} \quad \dots \quad \dots \quad (1)$$

While from this value and the fundamental equation (a) we get

$$r = \frac{(I - n)(W - w)}{I - W} \quad \dots \quad \dots \quad (2)$$

Further, by substituting these values for i and r in equation 17, and remembering that

$$i = \sqrt{\frac{(I - W)(I - w)r}{W - w}}$$

we have $$L = 2(I - i) - n \quad \dots \quad \dots \quad \dots \quad (3)$$

Equation 2 can also be written

$$r = \frac{I(W - w)}{I - W} - \frac{n(W - w)}{I - w} \quad \dots \quad (4)$$

Now we must remember that $2(I - i)$ is the corrected value of the conductor when the Resultant Fault is at the centre of conduction

Sometimes the line under test may even alter its condition during the three tests to such an extent that the values i, l, and L become not only incorrect, but entirely absurd.

In other words, the measurements made are unreliable, and must be rejected.

Thus it is required to have a check for these measured values, by which it is easily ascertained, without going into the final calculations, if they will give absurd results or not.

(see formula 20), which value we will designate by L', and, further, that $\frac{I(W - w)}{I - W}$ is the true value of the relay when the Resultant Fault is at the centre of conduction (see formula 21), and which value we will designate by r'. While $\sqrt{I(I - w)}$ is the corrected insulation by formula 19, which we will designate by i'.

Thus we may write the three formulæ 1, 2, and 3, as follows :—

$$i = \sqrt{I - n)(I - w)} = i' - \Delta \quad \ldots \quad (1)$$

$$r = r' - \frac{n(W - w)}{I - w} \quad \ldots \quad \ldots \quad (2)$$

$$L = L' - n \quad \ldots \quad \ldots \quad \ldots \quad (3)$$

Δ is a quantity which is positive when n is positive.

In these three equations the *true* corrected values are therefore expressed by the untrue corrected values and the displacement (n) of the Resultant Fault. These formulæ show at once what was to be proved, namely :—

that if n is positive,

$$i' > i$$
$$r' > r$$
$$L' > L$$

and if n is negative,

$$i' < i$$
$$r' < r$$
$$L' < L$$

These checks for the measured values are given by the following four inequalities :—

$$I > W > w \qquad \dots \qquad \dots \qquad 24\,[1]$$

$$1 < \frac{r}{W - w} \qquad \dots \qquad \dots \qquad 25\,[1]$$

$$\frac{I - w}{I - W} < \frac{r}{W - w} \qquad \dots \qquad \dots \qquad 26\,[1]$$

$$\frac{I^2}{(I - W)\,(I - w} > \frac{r}{W - w} \qquad \dots \qquad \dots \qquad 27\,[1]$$

Of these four the first two are very simple, and can be applied at once without the slightest calculation; they are what may be called *rough* checks, while the other two necessitate a slight calculation; however, by no

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[1] That the first two inequalities must be fulfilled follows at once from the three fundamental equations, and that the other two must be also fulfilled in addition can be easily shown, namely :—

By formulæ 17 and 18 we have

$$\frac{l}{L} = \frac{I - \sqrt{\dfrac{(I - W)\,(I - w)\,r}{W - w}}}{I + \dfrac{I - W}{I - w}\,r - 2\sqrt{\dfrac{(I - W)\,(I - w)\,r}{W - w}}}$$

Of the *ratio* $\frac{l}{L}$ we know that it must be invariably between unity and zero, and thus we have the following two inequalities :—

$$\frac{l}{L} < 1$$

and

$$\frac{l}{L} > 0$$

from the first it follows that,

$$\frac{I - w}{I - W} < \frac{r}{W - w} \qquad \dots \qquad (26)$$

and from the second,

$$\frac{I^2}{(I - W)\,(I - w)} > \frac{r}{W - w} \qquad \dots \qquad (27)$$

means as much as the formulæ themselves, and they may be said to be two *finer* checks.

XVII. *Scrutinising Tests.*—When scrutinising tests, the following routine may now be laid down :—

1. If the measured values do not fulfil inequality 24, the tests are unreliable, and must be rejected.
2. If the tests fulfil inequality 24, but not inequality 25, the tests are *not* to be rejected, only no corrections of the measured values must be made.

   In such a case the measured values must suffice as representing the electrical condition of the line ; and though they must be incorrect to a certain extent, we know, nevertheless, the sign of error made.
3. If inequalities 24 and 25 are both fulfilled, but not the other two, the measured values must be corrected by formulæ 19 and 20.
4. If the inequalities are all fulfilled, the measured values must be corrected by their proper formulæ, *i.e.*, either by 19 and 20, when the corrected relay corresponds within 10 per cent. with the real relay, or by formulæ 16 and 17, if this difference is greater than 10 per cent.

XVIII. *Additional Tests on a Double Line.*—On a double line the following additional tests can be made :—

1. The two lines being looped through the relays at the distant station, and the *earth* being thrown off from the testing arrangement, we can measure their joint "circuit" resistance.
2. The two lines being looped direct at the distant station, and the *earth* being thrown off from the

testing arrangement, we can measure their joint "conduction" resistance.

3. The two lines being looped direct at the distant stations, and one pole of the battery detached from the testing arrangement and put to earth, we can make the so-called "loop test," which determines the position of the Resultant Fault of the loop. We shall revert to this test when treating of "Fault Testing" in Section II.

The first two tests give very accurate results, provided that the bridge and battery are carefully insulated from the ground, since the *earth* of neither office is in circuit; and a single insulation fault in the loop, no matter of how low resistance, cannot influence the result.

The third test is of the greatest value, as it furnishes us with a means of localising very accurately any "partial earth," the resistance of which cannot be neglected against the absolute insulation of the loop.

It is not necessary to enlarge more on this subject here by enumerating the tests that can be made on lines having more than two wires. It will be sufficient to observe that the more wires connect two stations, the more easy is it for the tester to discover accurately the electrical condition of any of the lines between those stations.

APPENDIX I.

ON THE "RESULTANT FAULT."

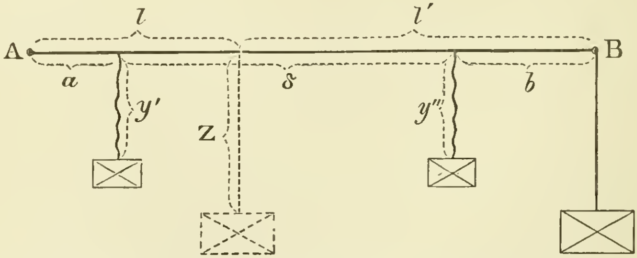
DEFINITION.—*The "Resultant Fault" of any line or cable is that fault which, if applied alone to the line at the proper point, would produce the same effects with respect to the sent and received currents, as all the actually existing faults do.*

The Resultant Fault has a determinate position and resistance. The corrected insulation gives the resistance of the "Resultant Fault."

In the following we will first develop the general formulæ for the resistance and position of the Resultant Fault as defined above, and then we will show how these expressions become simplified when presupposing certain conditions which are approximately fulfilled in line testing, and by which it will be proved at once that under these conditions the resistance and position of the Resultant Fault remain both constant during the three tests which can be made with a single line, viz., circuit test, conduction test, and insulation test.

We will suppose at first a line which contains only two faults, all the other points of the line being absolutely insulated from the earth.

If we put such a line with its distant end direct to earth, *i.e.*, executing the conduction test from station *A*, we have the following fig. :—



The small letters represent the resistances of the five branches, while the currents which flow through them shall be designated by capitals respectively.

Then we have obviously,

$$B = A \frac{y' y''}{(y' + \delta)(y'' + b) + by''}$$

Where B stands for the received current, and A for the sent current. If we, however, suppose only one fault with a resistance z at a distance l (measured in resistance) from the sending end A of the line, we have

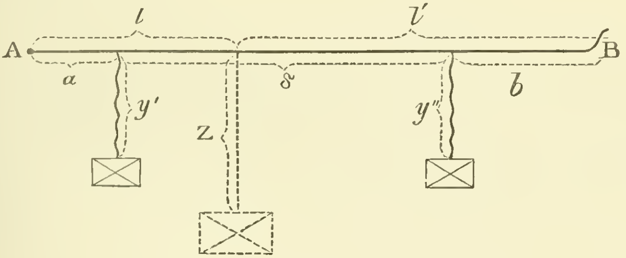
$$\frac{L z}{l' + z} = L' \qquad \text{(See fig :)}$$

where L' stands for the received current and L for the sent current. But according to definition :

$$L' = B$$
$$L = A$$

$$\therefore \quad \frac{y' y''}{(y' + \delta)(y'' + b) + by''} = \frac{z}{l' + z} \quad \cdots \quad \cdots \quad (1)$$

Further, if we insulate the line in question at its further end, we have the following fig. :—



$$\therefore \quad A = \frac{Constant}{a + \dfrac{y'(y'' + \delta)}{y' + y'' + \delta}}$$

while by supposing only one fault of resistance z, and in the same position as before, we have

$$L = \frac{Constant}{l + z}$$

but by definition

$$L = A$$

$$\therefore \quad a + \frac{y'(y'' + \delta)}{y' + y'' + \delta} = l + z \quad \cdots \quad \cdots \quad \cdots \quad \cdots \quad (2)$$

further, we have

$$a + \delta + b = l + l' \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (3)$$

and from these three equations l and z can be easily developed, namely :—

$$l = a + \frac{y' \delta}{y' + y'' + \delta} \cdot \frac{b(y' + \delta) + y'' b - y' y''}{b(y' + \delta) + y''(b + \delta) - y' y''} \quad \ldots \quad (4)$$

and

$$z = a - l + \frac{y'(y'' + \delta)}{y' + y'' + \delta} \quad \ldots \quad \ldots \quad \ldots \quad (5)$$

Now, we will suppose that the two existing faults y' and y'' are invariably so close together,[1] that δ can be neglected against b, when the right-hand factor in equation (4) approximates to unity very rapidly, and we have more simply :—

$$l = a + \frac{y' \delta}{y' + y'' + \delta} \quad \ldots \quad \ldots \quad \ldots \quad (6)$$

and this approximate value of l, substituted in equation 5 and reduced, we have

$$z = \frac{y' y''}{y' + y'' + \delta} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (7)$$

Now, as the line or cable under consideration is supposed to be in working condition, it is clear that y', as well as y'', must be so large that b can be neglected against either of them, consequently δ, as a very small part of b, can be still more neglected against the sum of the two faults, or we have at last :—

$$l = a + \frac{y' \delta}{y' + y''} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (8)$$

and $$z = \frac{y' y''}{y' + y''} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (9)$$

Equation 8 shows at once that the position of the Resultant Fault, within the two real faults in question, is independent of either a or b, and, consequently, that if the circuit test instead of the conduction test had been used, when only b would have altered,[2] the position of the Resultant Fault within the two real faults would have been expressed in the very same way; namely, also by formula 8.

Equation 9 shows that, under the supposed condition, the resistance of the Resultant Fault is always *equal to the parallel resistance of the two real faults ; i.e.*, equal to the corrected insulation.

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[1] In a line which is in working condition, *i.e.*, containing an innumerable number of faults, each of very great resistance, this supposition is always fulfilled.

[2] It is supposed that in the relay itself no leakage exists.

It remains now to generalise the results as given in 8 and 9, by developing a formula for the position of the Resultant Fault when any number of real faults exist, the resistances and positions of which are known, and to show that the resistance of the Resultant Fault in such a case is also represented by the parallel resistance of all the existing faults; *i.e.*, by the corrected insulation of the line.

To do this, we will write formula 8 differently, namely:—

$$l = \frac{r'' y' + r' y''}{y' + y''} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (10)$$

where y' and y'' are the resistances of the two real faults whose distances from the one end, A, of the line are r' and r'' respectively, measured in resistances. While l is the distance of the Resultant Fault from the same end, A, of the line, measured also in resistances.

Now, by supposing n faults in a line, we can easily calculate the position of the Resultant Fault by a continued application of formula 8; and to have an algebraical expression, we will call y the resistance of any fault whose distance from the same end, A, of the line is r, whence we have at once

$$l = \frac{\Sigma\left(\frac{r}{y}\right)}{\Sigma\left(\frac{1}{y}\right)} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (22)$$

as can be easily calculated, and which gives the position of the Resultant Fault when n real faults exist, while its resistance is evidently expressed by

$$z = \frac{1}{\Sigma\left(\frac{1}{y}\right)} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (23)$$

having only necessary to apply formula 9 continuously.

Supposing now that the number of faults becomes infinite ($n = \infty$), *i.e.*, that each point of the line contains a certain amount of leakage, which is practically true, and that, further, such a leakage along the whole of the line is represented by a certain continuous function $f(x)$, then the resistance of a fault in a point whose distance from the one end is x, can be expressed by

$$y = \frac{f(x)}{dx} \textit{ constant.}$$

Where x in this case is length, *not* resistance. Consequently, formula 22 becomes

$$l = Const. \frac{\int_{O}^{L} \frac{dx}{f(x)}\, r}{\int_{O}^{L} \frac{dx}{f(x)}} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (11)$$

or, taking also r to be a continuous function of x, we have most generally,

$$l = Const. \frac{\int_{O}^{L} \frac{dx}{f(x)}\, \psi(x)}{\int_{O}^{L} \frac{dx}{f(x)}} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (12)$$

and formula 9 becomes

$$z = \frac{Const.}{\int_{0}^{L} \frac{dx}{f(x)}} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (13)$$

and it must be understood that L means length, while l and z are expressed in resistances. The constant in each case must be determined, depending entirely on the system of units used for expressing length and resistance.

The general formulæ 12 and 13 are, however, not of practical interest since telegraph lines and telegraph cables are either uniform in conduction and insulation, or if not, the functions are *not* continuous. However, these formulæ have a mathematical importance in so far as they lead to interesting applications of the Integral Calculus. But it cannot be our purpose to give such examples here.

Formulæ 22 and 23 are, however, of practical value, and they are illustrated by examples in para. 14.

APPENDIX II.

ON THE EXECUTION OF REGULAR TESTS.

I. However much testing may become a matter of routine, it must always partake more or less of the nature of a physical experiment, and the practical results must depend on the right application of general rules to the circumstances of particular cases.

II. The objects of line testing are :—

- i. To ascertain which lines are good, and which defective.
- ii. To assure ourselves from time to time that the good lines are maintaining their normal condition.
- iii. To discover, with a view to removing, the causes of defectiveness in the imperfect lines.
- iv. To reduce the duration of interruptions.

It will be clear *à priori* that the limited amount of testing which will suffice for lines whose condition is known, and continues normal, may be altogether inadequate in the case of defective lines.

III. The *general rules* must, therefore, be :—

- i. In the case of good lines only periodical tests need be taken (at shorter or longer intervals, according to requirements), and then always of the *longest* section, as this single test will at once give the condition of all the intermediate sections, and consequently reduce the total number of tests requisite.
- ii. In the case of faulty sections, tests to discover the causes of the defects must be made at *such* times and with *such* frequency as the responsible officers may deem necessary.
- iii. Rules i. and ii. must always be subject to the indispensable condition of not interfering with traffic.
- iv. Special experiments, that may occupy the line for considerable periods, should be executed on Sundays between 8 and 16 hours, when the lines are generally free of traffic.

IV. To these general rules may here be added some *practical rules* included in them :—

i. All the lines terminating in a testing station are to be tested in accordance with the above general rules.

ii. As a rule, the tests of each wire are to be extended to such a point as to *bisect* the distance between *two* testing stations.

Exceptions to this rule are to be made when the testing stations are sufficiently near to admit of tests being extended from testing station to testing station.

iii. Another rule, which may be substituted for rule ii., is to test each wire as far as the testing station usually works it direct (*i.e.*, without translation), as from this single test all information necessary for traffic purposes is obtained.

This rule can obviously only be acted upon in the case of lines in good condition. For instance, it has been found by experience that the No. 1 wire between Bombay and Jubbulpore works perfectly well even during heavy rain; this wire should therefore be tested by Bombay and Jubbulpore direct to each other; section tests being only requisite should the results of the direct tests prove unsatisfactory. Bhosawul would not usually test this wire except on a Sunday, and then only for the purpose of securing the data necessary for the accurate localisation of faults.

On the other hand, the tests of the Bombay-Kurrachee main wire, although generally worked direct during the dry season, should never be extended from Bombay beyond Deesa, since the insulation of the section Hydrabad-Kurrachee, even during the best weather, is so low, owing to meteorological influences, as to entirely vitiate the results of such direct tests: during the rains, it will be scarcely advisable to test the main wire beyond Ahmedabad, while for the other two wires rules ii. and iii. may hold good.

iv. Divisional limits should never influence the extent of wire tested.

In order to be able to localise faults with accuracy, a very exact knowledge of the electrical and mechanical condition of each section is requisite, and this fact will serve as a guide to show in what sense the general rules given for regular testing are to be modified to meet the particular requirements of each testing station.

V. To obtain uniformity in the manner of conducting the regular testing of lines throughout India, and also to prevent loss of time, the following routine is to be invariably observed.

The tests of a line are to be executed in the following order:—

i. Circuit.
ii. Conduction.
iii. Insulation.

and no alteration of this order is permitted.

The signal "*test*" being given by the testing station, the signaller at the instrument of the out-station must at once call the telegraph master on duty, who is to remain in the office till testing is over, executing himself all the orders given by the testing station.

1st Signal.—"*Circuit.*" This means: *Leave your instrument alone till the name of the station is called by the testing station, and do not answer any unintelligible beats.*

This signal is to be invariably acknowledged by giving the "*Resistance of the Relay*" through which the test is to be made. Care must be taken that no other instruments besides the relay (such as galvanoscopes, shunts, &c.) are included in the circuit.

2d Signal.—"*Conduction, ten minutes.*" This means: *Put your line direct to earth at the commutator.*

This signal is to be acknowledged by giving the readings of the $\frac{\textit{wet}}{\textit{dry}}$ *bulb* thermometer, immediately after which the line must be put to earth for the time ordered. Care must be taken that the earth connection does not include any resistance that was not in circuit when taking the preceding test.

3d Signal.—"*Insulation, ten minutes.*" This means: *Insulate the line under test by taking out the plug at the commutator.*

This signal is to be acknowledged by giving the state of the weather (see Appendix VI.).

Here two other signals may be added, which are of frequent occurrence.

4th Signal.—"*Loop* Y *and* Z, *ten minutes.*" This means: *Connect the two lines named directly together at the commutator by properly shifting the plugs.*

This signal is to be acknowledged by giving "*Looped.*" Care must be taken that the looped lines are not in connection with their respective instruments, or with the earth.

5th Signal.—"*Join* D, *ten minutes.* This means: *Join the line under test in* D (direct), *but not in* G (galvanoscope), *for the time ordered.*

This signal is to be acknowledged by giving "*Joined.*" The line had best be joined in D at the commutator.

Any other orders that it may be found necessary to give when executing experiments required to establish facts concerning the lines under test, should always be given as briefly and distinctly as possible.

With the exception of the circuit test, all others have to be executed within a certain fixed period of time, and the telegraph master on duty should be exceedingly careful to accurately keep the time ordered. He should on no account open out before the time at which he was ordered to do so.

EXAMPLE.

Calcutta signals "*Test*" to Burdwan on the *B* line. The signaller at the instrument at once calls the telegraph master on duty, who gives his initials.

Calcutta signals "*Circuit.*" Burdwan gives the resistance of the relay marked on the instrument through which the *B* line is worked by Calcutta, and then leaves the instrument alone until Calcutta calls "Burdwan" on the *B* line.

Calcutta signals "*Conduction, two minutes.*" Burdwan replies on the *B* line by giving the readings of the $\frac{wet}{dry}$ thermometer; after which it puts the *B* line direct to earth, and does not open out until the two minutes are over.

Calcutta signals "*Insulation, five minutes.*" Burdwan replies with the weather (see Appendix VI.), and immediately takes out the plug at the commutator for the length of time ordered.

Calcutta signals "*Loop B and C, three minutes.*" Burdwan replies "*Looped,*" and connects the two lines named together at the commutator.

Calcutta signals "*Join D, fifteen minutes.*" Burdwan replies "*Joined,*" and joins *B* line in *D* (best at commutator), and on no account touches the line in question before the time ordered has elapsed.

APPENDIX III.

ON THE COMPUTATION OF REGULAR TESTS.

I. The first point for any officer to examine, when a test sheet is before him, is the *physical possibility of the experimental results recorded therein;* that is, he must go through the sheet, and see that in the case of each line the six measured values (one + and one − in each of the three tests: "circuit," "conduction," and "insulation") are consonant and rational.

The checks to be applied are as follows:—

1st Criterion.

i. In the case of the "circuit" and "conduction" tests, if in the tests of one line w' (the resistance producing balance when testing with positive current) is *greater* than w'' (the resistance producing balance when testing with negative current), and the deflection noted on the galvanometer needle,[1] as due to the natural current, is to the *left*, then, provided the galvanometer terminals are not reversed, the deflection must, in the tests of all other lines, be to the *left* whenever w' is *greater* than w'', and *vice versâ.*

ii. In the case of insulation tests, the resistance measured with copper to line (positive test current) is almost invariably greater than the resistance measured with zinc to line (negative test current). Any deviation from this rule can only occur when the insulation is exceedingly low, or the line is faulty.

II. *Electromotive force in Line.*—Having seen that the measurements are possible, and that the natural current did not change during the + and − tests, calculate e, the electromotive force in the line, by formula (5) of the Testing Instructions:—

i. From the "conduction" test only, provided the current observed during the "circuit" test is the same in direction, and approximately equal in magnitude to that observed during the "conduction" test.

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[1] See Part II., Section I., p. 64.

ii. From both the "circuit" and the "conduction" tests, when the currents observed in the two cases are different.

The labour of this, and many subsequent calculations, may be reduced by using a table of logarithms.

Formula (5) stands thus :—

$$\frac{e}{E} = \frac{w'' - w'}{w' + w'' + 2\,(2\,f + a)}$$
$$= N \text{ say.}$$

First find $log\ (w'' - w')$ and then from it subtract the logarithm of $w' + w'' + 2\ (2\,f + a)$, which will give $log \frac{w'' - w'}{w' + w'' + 2\,(2\,f + a)}$ $= log\ N$. To this add $log\ E$, which will give the logarithm of the whole expression $N\ E$, and then find the corresponding number from the tables, and give it to at least two places of decimals : this will be the natural *E. M. F.*, in terms of that of the testing battery. Never calculate e from the "insulation" test, unless there be some special reason for doing so.

III. *The "measured circuit," the "measured conduction," and the "measured insulation" resistances.*—Proceed to find W and w from the circuit and conduction tests respectively, using formula (8) :

i. For resistances under 1000 when the difference is less than 20 per cent.

ii. For resistances from 1000 to 5000 when the difference is less than 15 per cent.

iii. For resistances greater than 5000 when the difference is less than 10 per cent, but in all other cases using formula (2), (4), or (6).

Formula (2), which is absolutely true when the natural current has not varied during the test, may be more simply written, thus—

$$x = \frac{b}{a}\left\{\frac{w' + w''}{2} - \frac{b\,(w'' - w')^2}{2\,b\,(w' + w'') + 4\,f\,(a + b) + 4\,a\,b}\right\}$$

and when $a = b$ (as is almost invariably the case in the circuit and conduction tests)

$$x = \frac{w' + w''}{2} - \frac{(w'' - w')^2}{2\,(w' + w'') + 4\,(2\,f + a)}$$
$$= \frac{w' + w''}{2} - N\frac{w'' - w'}{2}$$

As we already know, $log\ N$ and $log\ (w'' - w')$, we add them together, and subtract $log\ 2$ ($= 0{\cdot}3010300$) from the result, which will give us $log\left(N\frac{w'' - w'}{2}\right)$. We then find the corresponding number from the tables, and subtract it from the mean of w' and w'', which will give us x.

To find the mean of w' and w'', the simpler process is, not to add w' to w'', and divide by 2, but to take half of the difference $w'' - w'$ (which is already known), and subtract it from the larger or add it to the smaller number.

To find the measured insulation I, always use formula (8). First find the mean as above, and multiply the result by $\frac{b}{a}$. As $\frac{b}{a}$ is always 1, 10, 100, or 1000, no trouble will be experienced in doing this.

IV. Having thus found the values of W, w, and I, we must examine whether the following inequality holds: 2nd Criterion.

$$w < W < I$$

If this is not the case, no further accurate calculations can be based on the measurements; but if the necessary inequality holds, then:—

V. Find the "measured" relay, *i.e.*, the difference between W and w; and reduce (if necessary) the marked resistance of the relay at the distant station, through which the circuit test was taken, to the resistance corresponding to the temperature at which the test was made; which is to be done by means of the following formula:—

$$R_{t'} = \frac{1 + (t' - 32)\,a}{1 + (t - 32)\,a} R_t$$

where $R_{t'}$ is the required resistance,

R_t is the marked resistance,

t' is the temperature in degrees Fahr. at which the test was made,

t is the temperature in degrees Fahr. at which the instrument was marked,

and a is the rate of increase of resistance per degree Fahr. ($= 0{\cdot}0021$ for copper wire).

As the relays on the several circuits are not frequently changed, it is advisable to prepare a table showing the resistances of the relays at different temperatures within a practical range. The instruments now issued from stock are all marked at 80° Fahr.; and to facilitate the preparation of the above table, a table for converting any resistances from 80° Fahr. to any other temperature between 55° Fahr. and 110° Fahr. is annexed. (*Vide* Note A.)

Denoting by r the resistance of the relay at the distant station (corrected to the temperature at the time of testing), then it will almost invariably be found that

$$W - w < r$$

Never under any circumstances should we have

$$W - w > r$$

But, occasionally, when the line is short, and its insulation resistance so great that the conduction resistance may be neglected against it, we may find that approximately

$$W - w = r$$

3d Criterion. In practice, when it is found either that $W - w > r$, or that $W - w = r$, we have the following two rules to guide us :—

i. If the insulation resistance is so great that the conduction resistance may be neglected against it, then we make no further calculations (since in the one case calculations are impossible, and in the other they are unnecessary), but we accept the "measured" values and use them in place of the "corrected."

ii. If the insulation resistance is *not* so great that the conduction resistance may be neglected against it, then the tests are untrustworthy, and must be employed with caution.

VI. When $W - w < r$ (the general case), we must proceed to correct the "measured" values in order to find the "real" conduction and insulation.

To do this, formulæ (16) and (17) must be employed—time and labour will be lost by using other formulæ.

The expression for the corrected insulation is

$$i + \sqrt{\frac{(I - W)(I - w)r}{W - w}}$$

First find $log\ (I - W)$, add it to $log\ r$, and from the result subtract $log\ (W - w)$: this will give $log\ \frac{(I - W)r}{(W - w)}$. To this add log (I $- w$), divide by 2, and from the tables find the number corresponding to the result: this will be i.

The expression for L is

$$L = I + \frac{(I - W)r}{W - w} - 2\sqrt{\frac{(I - W)(I - w)r}{W - w}}$$

$$= I + \frac{(I - W)r}{W - w} - 2i$$

There will be no difficulty in evaluating this, since i and log $\frac{(I - W)r}{W - w}$ are already known.

We can then, also, at once find l, for

$$l = I - i$$

VII. Having thus found the "real" conduction resistance of the line (L), the "real" insulation resistance (i), and the resistance l from the testing station to the "resultant fault," we must proceed to examine these results.

i may be greater than, equal to, or less than L, depending on the length and insulation of the line. However, on all well-insulated lines, not extremely long, it will be found that

$$i > L$$

It is scarcely necessary to say that i must never be greater than I, or L smaller than w.

l must always be between 0 and L; but between these limits it may have any value, since the "resultant fault" may be at any point of the line. If the "resultant fault" is in the testing station, then $l = 0$, $i = I$, and $L > w$; if the "resultant fault" is in the distant station, then $l = L$, $i < L$, and $L = w$; and finally (the general case), if the "resultant fault" be at any point of the line not indefinitely near to either station, then $l < L$, $i < I$, $L > w$.

4th Criterion.

The simplest criterion of the truth of the "corrected" values is afforded by the ratio $\frac{l}{L}$ which must always be positive, and *not* greater than 1.

It can always be seen by inspection whether the ratio $\frac{l}{L}$ fulfils the above conditions or not; and then

i. If $\frac{l}{L}$ is positive and not greater than 1, evaluate the ratio by logarithms to three places of decimals.

The values of i and L as found above will be true.

ii. If $\frac{l}{L}$ is negative or greater than 1, evaluate the ratio roughly by ordinary division.

The values of i and L as found above must be rejected, and other values found from the following two equations:—

$$\log i = \tfrac{1}{2}\{\log I + \log(I - w)\}$$
$$L = 2(I - i)$$

These values, though not absolutely true, are more correct than the mere "measured" values.

VIII. Having thus found the "corrected" *absolute* conduction and insulation of the line, the next step is to find the "corrected" conduction and insulation *per mile.*

The conduction resistance per mile of the standard wire is expressed in ohms, and is found by dividing L the absolute conduction resistance of the line by a certain number m, representing what Ohm called the "reduced length" of the line—*i.e.*, the length in miles of the standard wire that would have the same resistance as the actual line: in practice, No. 50 I. W. G. is taken as the standard.

The insulation per mile is expressed in megohms, and is found by multiplying i the absolute insulation by n the number of miles the line is in length.

Much time and labour may be saved in effecting these calculations by the use of a table previously prepared for the line under test. (*Vide* Note B.) The table gives at once, without any calculation, the results correct to the first place of decimals, and this will be almost always sufficient. The only exception will be when the insulation is very low; and then it may be necessary, in the case of the insulation per mile, to obtain the result correct to the second place of decimals, which can be done by a slight calculation, with the aid of the figures at the top of the table.

IX. It should be noted by testing officers:—

i. That when W or w is found from the two measured values (the one positive and the other negative) by means of formula (8), viz.:—$w = \frac{b}{a} \cdot \frac{w' + w''}{2}$, then the E. M. F. in the line *need not* be calculated out, as in such cases it is necessarily very small; but its direction must invariably be noted.[1]

ii. That when the measured values are corrected by means of formulæ (14) and (15), and it has been ascertained that $\frac{l}{L}$ is positive, and not $>$ 1, then the relay resistance *need not* be calculated out by means of formula (19), viz: $r = \frac{I(W - w)}{I - W}$ for the former check is quite sufficient of itself.

iii. That when, on the other hand, $\frac{l}{L}$ is negative or $>$ 1, the measured values must be corrected by means of formulæ (17) and (18); and the relay resistance must be calculated by formula (19), since the latter constitutes the only check now available.

iv. That when the insulation is so high that the measured values require no correction, then the resistance of the relay at the distant station *need not* be corrected for temperature (as this is obviously unnecessary), nor need its value be calculated by formula (19).

v. Finally, that when the insulation is beyond the range of measurement of the bridge, clearly no corrections of the measured values are ever to be made.

X. The formulæ employed are extremely sensitive, so that, unless the calculations are based on really good observations, the results arrived at are misleading. Consequently, if the lines are disturbed at the time of testing, owing to the insulation being low and variable, or to the existence of faults on the line, or to the occurrence of strong and variable natural currents, or generally if the condition of the line be not steady and normal, the corrected conduction resistance is apt to be too high or too low.

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[1] When $w' > w''$ the natural E. M. F. is negative; when $w' < w''$ the natural E. M. F. is positive.

When results that are manifestly too low are obtained, they are only physically possible if the gauges of the wire on the line are incorrectly stated—*i.e.*, if the wire is thicker, and consequently more conducting than is supposed—but if it be certainly known that the gauges of wire are correctly given, then such results are physically impossible, and must be at once struck out by the compiling officer. For example, if a line is known to consist of No. 24 wire, and the corrected conduction comes out 8 ohms at 80° or 90° Fahr., this result is, on the face of it, to be rejected from the average, since it is manifestly too low.

In the rejection of results that are too high, however, great caution must be exercised; for the high resistance observed may possibly be due to a real want of continuity somewhere in the circuit.

Generally, if a high result is due to simply unfavourable observations, there will be something in the test itself, which can be found by careful scrutiny, that will indicate the fact most clearly; and, under these circumstances, we are justified in omitting the result from the average. If, however, there is nothing in the test itself to show that the measurements were made badly, or under unfavourable conditions, the result must be retained, and included in the average; and obviously, then, the persistent recurrence of such results can be only due to a real discontinuity in the circuit.

The use of an incorrect value of the relay resistance in the formulæ will entail absurd results, and must be carefully guarded against.

NOTE A.

TABLE showing the different resistances at different temperatures between 55° and 110° Fahr. of a relay whose resistance at 80° Fahr. is 812·5.

Tempera-ture.	RELAY.		Tempera-ture.	RELAY.	
	Resistance.	Logarithm.		Resistance.	Logarithm.
55°	773·744	2·8886029	83°	817·198	2·9123272
56°	775·297	2·8894681	84°	818·761	2·9131571
57°	776·852	2·8903378	85°	820·324	2·9139854
58°	778·395	2·8912000	86°	821·888	2·9148126
59°	779·948	2·8920100	87°	823·451	2·9156377
60°	781·239	2·8927839	88°	825·015	2·9164618
61°	782·802	2·8936520	89°	826·578	2·9172837
62°	784·366	2·8945186	90°	828·141	2·9181043
63°	785·929	2·8953834	91°	829·705	2·9189237
64°	787·493	2·8962465	92°	831·268	2.9197410
65°	790·056	2·8970673	93°	832·832	2·9205574
66°	790·619	2·8979675	94°	834·395	2·9213727
67°	792·183	2·8988254	95°	835·958	2·9221844
68°	793·746	2·8996817	96°	837·522	2·9229962
69°	795·310	2·9005363	97°	839·085	2·9238060
70°	796·873	2·9013892	98°	840·649	2·9246147
71°	798·436	2·9022404	99°	842·212	2·9254214
72°	800·000	2·9030900	100°	843·775	2·9262267
73°	801·563	2·9039379	101°	845·339	2·9270308
74°	803·127	2·9047842	102°	846·902	2·9278331
75°	804·690	2·9056288	103°	848·466	2·9286344
76°	806·254	2·9064717	104°	850·029	2·9294336
77°	807·817	2·9073130	105°	851·592	2·9302316
78°	809·380	2·9081477	106°	853·156	2·9310284
79°	810·944	2·9089908	107°	854·719	2·9318233
80°	812·507	2·9098271	108°	856·283	2·9326173
81°	814·071	2·9106623	109°	857·846	2·9334093
82°	815·634	2·9114953	110°	859·409	2·9341998

TABLE, to accompany Note A, for converting the resistance of copper wire measured at 80° Fahr. to the corresponding resistance at any temperature between 55° and 110° Fahr.

Temperature.	10,000	20,000	30,000	40,000	50,000	60,000	70,000	80,000	90,000
55°	9523	19046	28570	38094	47615	57138	66663	76185	85708
56°	9542	19085	28627	38170	47710	57253	66796	76337	85879
57°	9561	19123	28684	38246	47805	57367	66929	76490	86051
58°	9580	19161	28741	38322	47901	57482	67063	76642	86223
59°	9599	19199	28798	38398	47997	57596	57196	76795	86394
60°	9618	19237	28855	38474	48092	57711	67329	76948	86566
61°	9638	19275	28913	38550	48188	57825	67463	77100	86738
62°	9657	19313	28970	38626	48283	57940	67596	77253	86909
63°	9676	19351	29027	38703	48378	58054	67729	77406	87081
64°	9695	19390	29084	38779	48474	58169	67863	77558	87253
65°	9714	19428	29142	38855	48569	58283	67997	77711	87425
66°	9733	19466	29199	38932	48665	58398	68130	77863	87596
67°	9752	19504	29256	39008	48760	58512	68264	78016	87768
68°	9771	19542	29313	39084	48855	58626	68398	78169	87940
69°	9790	19580	29370	39161	48951	58741	68531	78321	88111
70°	9809	19618	29428	39237	49046	58855	68665	78474	88283
71°	9828	19657	29485	39313	49142	58970	68798	78626	88455
72°	9847	19695	29542	39390	49237	59084	68932	78779	88626
73°	9866	19733	29599	39466	49832	59199	69065	78932	88798
74°	9886	19771	29657	39542	49428	59313	69199	79084	88970
75°	9905	19809	29714	39618	49523	59428	69332	79237	89141
76°	9924	19847	29771	39695	49618	59542	69466	79390	89313
77°	9943	19896	29828	39791	49714	59657	69599	79542	89485
78°	9962	19924	29886	39847	49809	59771	69733	79695	89657
79°	9981	19962	29943	39924	49905	59886	69896	79847	89828
80°	10000	20000	30000	40000	50000	60000	70000	80000	90000
81°	10019	20038	30057	40076	50095	60114	70134	80135	90172
82°	10038	20076	30114	40153	50191	60229	70267	80305	90343
83°	10057	20114	30172	40229	50986	60343	70401	80458	90515
84°	10076	20153	30229	40305	50382	60458	70534	80610	90687
85°	10095	20191	30286	40382	50477	60572	70668	80763	90858
86°	10114	20229	30343	40458	50572	60687	70801	80916	91030
87°	10134	20267	30401	40534	50668	60801	70935	81068	91202
88°	10153	20305	30458	40610	50763	60916	71068	81221	91374
89°	10172	20343	30515	40687	50858	61030	71202	81374	91545
90°	10191	20382	30572	40763	50954	61145	71335	81526	91717
91°	10210	20420	30630	40839	51049	61259	71469	81679	91889
92°	10229	20458	30687	40916	51145	61374	71602	81831	92060
93°	10248	20496	30744	40992	51240	61488	71736	81904	92232
94°	10267	20534	30801	41068	51335	61602	71870	82137	92404
95°	10286	20572	30858	41145	51431	61717	72003	82289	92575
96°	10305	20610	30916	41221	51526	61831	72137	82442	92747
97°	10324	20649	30973	41297	51621	61946	72270	82594	92919
98°	10343	20687	31030	41374	51717	62060	72404	82747	93090
99°	10362	20725	31087	41450	51812	62175	72537	82900	93262
100°	10382	20763	31145	41526	51907	62288	72671	83052	93434
101°	10401	20801	31202	41602	52003	62404	72804	83205	93606
102°	10420	20839	31259	41679	52098	62518	72938	83358	93777
103°	10439	20878	31316	41755	52194	62633	73071	83510	93949
104°	10458	20916	31374	41831	52289	62747	73205	83663	94121
105°	10477	20954	31431	41908	52385	62862	73338	83815	94292
106°	10496	20992	31488	41984	52480	62976	73472	83968	94464
107°	10515	21030	31545	42060	52575	63090	73605	84121	94636
108°	10534	21068	31602	42137	52671	63205	73739	84273	94807
109°	10553	21106	31660	42213	52766	63319	73873	84426	94979
110°	10572	21145	31717	42289	52862	63434	74006	84578	95151

$$R_x = \left\{ 0{\cdot}9084 + 0{\cdot}0019\,(x-32) \right\} R_{80}$$

NOTE B.

TABLE for the finding per mile Conduction and Insulation from the absolute.

This table is troublesome to prepare, but, when once completed, saves an immensity of labour.

The following is an explanation of the theory on which it is based, the way to use it, and how to prepare it.

Theory of the Table.

First with regard to conduction.

Let r = resistance per mile of No. 50 wire.
ar = ,, ,, No. 48 ,,
$\dots$ = ...
nr = ,, ,, No. n ,,
l = No. of miles of No. 50 wire on the line.
l_2 = ,, ,, No. 48 ,, ,,
$\dots$ = ...
l_n = ,, ,, No. n ,, ,,
L = absolute conduction resistance of the line.
Then $L = lr + l_2\,ar + \cdots\cdots + l_n\,n\,r\cdots\cdots$
$= r\,(l + a\,l_2 + \cdots\cdots + n\,l_n + \cdots\cdots)$
$= rm$

a number which remains constant for each line so long as the lengths and gauges of the wire composing it are not altered, and which Ohm called the "reduced length" of the line.

For example, the line from X to Y consists of

Miles $124\frac{3}{4}$ of No. 50.
,, $104\frac{1}{2}$ of No. 24.
,, $1\frac{1}{2}$ of No. 16.
,, 2 of No. 6.

Therefore, in this case,

$$m = 124\tfrac{3}{4} + 104\tfrac{1}{2}\,a + 1\tfrac{1}{2}\,b + 2\,c$$

The numbers a, b, c—expressing the ratios of the resistance per mile of Nos. 24, 16, and 6 to the resistance per mile of No. 50 wire—are to be found from the table annexed to this Note, in framing which it has been assumed that the specific resistance of all gauges is the same, so that the numbers a, b, c, &c., are simply inversely as the weights per mile of the wires. In the example given—

$$\begin{aligned} m &= 124{\cdot}75 + 104{\cdot}5 \times 2{\cdot}084 + 1{\cdot}5 \times 3{\cdot}125 + 2 \times 8{\cdot}333. \\ &= 363{\cdot}88 \text{ miles} = \text{reduced length.} \end{aligned}$$

Obviously m need only be calculated once for all for each line, so long as no alteration is made in the wire of which it consists.

Knowing m the reduced length of the line, and having found L the corrected absolute conduction resistance, we can at once, by simply dividing the latter from the former, obtain r the resistance per mile of No. 50 wire; *i.e.*—

$$r = \frac{L}{m}$$

And having found r, we can find the resistance per mile of any other gauge, if desired, by multiplying by the suitable coefficient a, b, c............taken from a table of ratios.

When there are a number of different gauges on a line, the per mileage resistance of *one* gauge *only* need be calculated. In practice it is best and most convenient to select No. 50 wire.

Secondly, with regard to insulation, since it is independent of the gauges of wire, we have simply to multiply the absolute corrected insulation (i) by the number of miles (n) in the line in order to obtain (J) the insulation per mile; thus—

$$J = n\,i.$$

How to Use the Table.

The object of the table is to do away with the operations $L \div m$ and $i \times n$—that is, to allow us, by simple reference to the table, having found the absolute conduction and insulation, to at once write down the conduction and insulation per mile.

Referring to the sample table given, the heading sufficiently explains itself. The Ionic figures in the 2d, 3d, and 4th columns refer to conduction only, the ordinary figures under the heads 1 to 9 to insulation only, and the decimals in the first column to both conduction and insulation.

Giving our attention to the Ionic figures first, the figures 4, 5, and 6 heading the columns are integral parts of the per mile resistance of No. 50 wire (whose resistance is never less than 4 ohms, or greater than 7 ohms), whilst in the outer left-hand column the fractional parts are given to two places of decimals. For example, if $L = 1674$, we find 4 at the head of the column in which this number occurs, and ·60 opposite it, to its left, in the fractional column; hence the required per mile resistance is 4·60. Similarly, if the absolute conduction is 1910, the per mile resistance is 5·25; and if 2474, the per mile resistance is 6·80. When the absolute conduction resistance is expressed by a number which does not actually occur in the table, we must look for the next nearest number; for instance, if $L = 1941$, then the nearest number to this that occurs in the table is 1947 (corresponding to a mileage of 5·35), which is too large by 6. At the top (above the figures 4, 5, 6) we see that the number most nearly approaching to 6 is 7·32 (corresponding to a mileage of 0·02). Hence the correct mileage is $5{\cdot}35 - 0{\cdot}02 = 5{\cdot}33$.

The insulation per mile is found in a similar manner. For example, if $i = 19550$, then we find 19549 in the column under the integer 4 and opposite the fractional part (in the left outer column) ·55; hence $J = 4·55$. Similarly we find that

if $i = 24060$ then $J = 5·60$
„ $i = 42750$ „ $J = 9·95$
„ $i = 32610$ „ $J = 8·59$

When the absolute insulation is beyond the range of the table, we must, in the first place, divide it by 10 or 100, as the case may demand, find the per mile insulation corresponding to the quotient, and multiply the result by 10 or 100. Should any figures still remain that were not taken into consideration, and which we do not wish to neglect, then we must find the mileage corresponding to this remainder, and add it to the first result. For example, suppose the absolute insulation is 256900—here to divide by 10 will be sufficient, giving a quotient 25690—we find the number 25564 in the column under the head 5, and opposite the fraction 0·95 corresponding to an insulation per mile of 5·95, and multiplying by 10 we have 59·5. If, now, we wish to take the remainder into consideration, we observe that the difference between 256900 and 259640 = 1260. The number 1260 is again out of the range of the table, being smaller than any number found therein. Multiplying it, however, by 10, we have 12600; and at the bottom of the column headed 2 we find 12675, corresponding to a per mile resistance of 2·95. Since we multiplied the number by 10, we must divide the result by 10, thus obtaining 0·295 per mile. Hence the correct mileage is 59·5 + 0·295 = 59·8. This degree of accuracy is not, however, generally required.

How to Prepare the Table.

A separate table need not always be prepared for each line; for the conduction portion of a table, prepared for any line, is applicable to *all* lines of the same reduced length, m; and the insulation portion of a table, prepared for any line, is applicable to *all* lines of the same actual length, n.

For example, one and the same insulation table would apply to all four of the Allahabad Jubbulpore lines, since they are all 229 miles in length; and one and the same conduction table would apply to the Allahabad Jubbulpore B and J lines, since for both these lines $m = 487$.

Firstly, with regard to the conduction portion of the Table.

Multiply m by 4, and increase the result 59 times by $0·05\ m$. The 60 results thus obtained will give the 60 numbers found in the three columns under the heads 4, 5, 6. For example, in the specimen table, $m = 363·88$. The first number, therefore, is $363·88 \times 4 = 1455·5$; the second is $1455·5 + 363·88 \times 0·05 = 1455·5 + 18·19 = 1474$; the third is $1474 + 18 = 1492$; and so on.

In going from one to the next of any of these 60 numbers, the conduction per mile varies by 0·05 ohm, as is seen from the first column of the table; but the numbers corresponding to 0·01, 0·02, 0·03, 0·04 ohm per mile are given above the figures 4, 5, 6, so that we can always find the resistance per mile to two places of decimals almost exactly.

From its mode of development we see that the figures in this part of the table depend on the absolute value of the "reduced length" m, and on no other quantity. It is therefore applicable to *all* lines of the same reduced length.

Secondly, with regard to the insulation portion of the Table.

Divide 1,000,000 by n the length of the line in miles, and increase the result 179 times by $\frac{1,000,000 \times 0\cdot05}{n}$. The 180 results thus obtained will give the 180 numbers found in the 9 columns under the heads 1, 2, 3, 4, 5, 6, 7, 8, and 9. For example, in the case of the table given herewith $n = 232\cdot75$. The first number, therefore, is $\frac{1000000}{232\cdot75} = 4296$; the second is $4296 + 4296 \times 0\cdot05 = 4296 + 214\cdot8 = 4511$; the third is $4511 + 215 = 4726$; and so on.

Hence from its mode of development we see that this part of the table depends on the number of miles n the line is in length, and on no other quantity. It is therefore applicable to *all* lines of the same length.

Table, to accompany Note B, for finding the per mile resistance from the absolute.

Line from X *to* Y. *Miles :* 232·75. *Gauges ;* 2 *Miles of No.* 6, 1·5 *of* 16,104·5 *of* 24, *and* 124·75 *of* 50 . · . *M* = 363·88.

	·01=3·66 ·03=10·98 ·02=7·32 ·04=14·64			·01 = 43		·02 = 86		·03 = 129			·04 = 172	
	4	5	6	1	2	3	4	5	6	7	8	9
·00	1456	1819	2183	4296	8593	12889	17186	21842	25775	30075	34372	38668
·05	74	38	2201	4511	8807	13104	7401	1697	5994	0290	4586	8883
·10	92	56	20	4726	9023	3319	7615	1912	26204	0505	4801	39098
·15	1510	74	38	4941	9237	3534	7830	22127	6423	0720	35016	9313
·20	28	92	56	5156	9452	3749	18045	2342	6638	0934	5233	9527
·25	46	1910	74	5311	9667	3963	8260	2556	6853	31149	5446	9742
·30	65	28	92	5585	9882	14176	8475	2771	27068	1364	5661	9957
·35	83	47	2311	5800	10096	4393	8689	2986	7282	1579	5875	40172
·40	1601	65	29	6016	0311	4608	8904	23201	7497	1794	36090	0387
·45	19	83	47	6230	0526	4823	19119	3416	7712	32008	6305	0601
·50	37	2001	65	6445	7041	15038	9334	3631	7927	2223	6520	0816
·55	56	19	83	6660	0956	5252	9549	3845	28142	2438	6735	41031
·60	74	38	2402	6874	11171	5467	9764	24060	8357	2653	6950	1246
·65	92	56	20	7089	1386	5682	9978	4275	8571	2868	37164	1461
·70	1710	74	38	7304	1601	5897	20193	4489	8786	33083	7379	1676
·75	28	92	56	7519	1815	16112	0408	4705	29001	3297	7594	1890
·80	47	2110	74	7734	12030	6327	0623	4919	9216	3512	7809	42105
·85	65	29	92	7948	2245	6541	0838	25134	9431	3727	38024	2320
·90	83	47	2511	8163	2460	6756	21093	5349	9646	3942	8238	2535
·95	1801	65	29	8378	2675	6971	1267	5564	9860	34157	8453	2749

TABLE to accompany Note B. Indian Telegraph Iron Wire Gauge.

Gauge.	Weight in lbs., per			Diameter in $\frac{1}{1000}$ inch	Area of section in $\frac{1}{10000}$ sq. inch.	Breaking strain in lbs.	Resistance per mile in ohms at 80° F.	Ratio of the resistance in terms of No. 50 wire.
No.	Mile.	Yard.	Foot.					
1	25	·0142	·0047	42	14	83	252·00	50·000
2	50	·0284	·0095	60	28	167	126·00	25·000
3	75	·0426	·0142	75	43	250	84·00	16·667
4	100	·0568	·0189	85	57	333	63·00	12·500
5	125	·0710	·0237	95	71	417	50·40	10·000
6	150	·0852	·0284	104	85	500	42·00	8·333
7	175	·0994	·0331	112	99	583	36·00	7·143
8	200	·1136	·0379	120	114	697	31·50	6·250
9	225	·1278	·0426	127	128	750	28·00	5·556
10	250	·1420	·0473	134	142	833	25·20	5·000
11	275	·1562	·0521	140	156	917	22·91	4·545
12	300	·1705	·0568	147	170	1000	21·00	4·167
13	325	·1847	·0616	153	184	1083	19·38	3·846
14	350	·1989	·0663	159	198	1167	18·00	3·572
15	375	·2131	·0710	166	213	1250	16·80	3·334
16	400	·2273	·0758	170	227	1333	15·75	3·125
17	425	·2415	·0805	175	241	1417	14·82	2·941
18	450	·2557	·0852	180	255	1500	14·00	2·778
19	475	·2699	·0900	185	270	1583	13·26	2·632
20	500	·2841	·0947	190	284	1667	12·60	2·500
21	525	·2983	·0994	195	298	1750	12·00	2·381
22	550	·3125	·1042	200	312	1833	11·45	2·273
23	575	·3267	·1089	204	326	1917	10·96	2·174
24	600	·3409	·1136	208	341	2000	10·50	2·084
25	625	·3551	·1184	212	355	2083	10·08	2·000
26	650	·3693	·1231	217	369	2167	9·78	1·923
27	675	·3835	·1278	221	383	2250	9·33	1·852
28	700	·3977	·1326	225	397	2333	9·00	1·786
29	725	·4119	·1373	229	412	2417	8·67	1·724
30	750	·4261	·1420	233	426	2500	8·40	1·667
31	775	·4403	·1468	237	440	2583	8·13	1·613
32	800	·4545	·1515	240	454	2667	7·87	1·563
33	825	·4687	·1562	244	468	2750	7·64	1·515
34	850	·4830	·1610	248	483	2833	7·41	1·471
35	875	·4972	·1657	251	497	2917	7·20	1·429
36	900	·5114	·1704	255	511	3000	7·00	1·389
37	925	·5256	·1752	258	525	3083	6·81	1·352
38	950	·5398	·1799	262	539	3167	6·63	1·316
39	975	·5540	·1846	265	554	3256	6·46	1·282
40	1000	·5682	·1894	269	568	3333	6·30	1·250
41	1025	·5824	·1941	272	582	3417	6·15	1·220
42	1050	·5966	·1989	275	596	3500	6·00	1·191
43	1075	·6108	·2036	279	610	3583	5·86	1·163
44	1100	·6252	·2083	282	624	3667	5·73	1·137
45	1125	·6394	·2131	285	639	3750	5·60	1·111
46	1150	·6536	·2178	289	653	3833	5·48	1·087
47	1175	·6678	·2225	291	667	3917	5·36	1·064
48	1200	·6820	·2273	294	681	4000	5·25	1·042
49	1225	·6962	·2320	297	695	4083	5·14	1·021
50	1250	·7104	·2367	300	710	4167	5·04	1·000

TABLE to accompany Note B. For converting Siemens and B. A. Units.

B. A. U.	S. U.	B. A. U.	S. U.	B. A. U.	S. U.	B. A. U.	S. U.	B. A. U.	S. U.
1	1·0486	21	22·0206	41	42·9926	61	63·9646	81	84·9366
2	2·0972	22	23·0692	42	44·0412	62	65·0132	82	85·9852
3	3·1458	23	24·1178	43	45·0898	63	66·0618	83	87·0338
4	4·1944	24	25·1664	44	46·1384	64	67·1104	84	88·0824
5	5·2430	25	26·2150	45	47·1870	65	68·1590	85	89·1310
6	6·5216	26	27·2636	46	48·2356	66	69·2076	86	90·1796
7	7·3402	27	28·3122	47	49·2842	67	70·2562	87	91·2282
8	8·3888	28	29·3608	48	50·3328	68	71·3048	88	92·2768
9	9·4374	29	30·4094	49	51·3814	69	72·3534	89	93·3254
10	10·4860	30	31·4580	50	52·4300	70	73·4020	90	94·3740
11	11·5346	31	32·5066	51	53·4786	71	74·4506	91	95·4226
12	12·5832	32	33·5552	52	54·5272	72	75·4992	92	96·4712
13	13·6318	33	34·6038	53	55·5758	73	76·5478	93	97·5198
14	14·6804	34	35·6524	54	56·6244	74	77·5964	94	98·5684
15	15·7290	35	36·7010	55	57·6730	75	78·6450	95	99·6170
16	16·7776	36	37·7496	56	58·7216	76	79·6936	96	100·6656
17	17·8262	37	38·8982	57	59·7702	77	80·7422	97	101·7142
18	18·8748	38	39·8468	58	60·8188	78	81·7908	98	102·7628
19	19·9234	39	40·8954	59	61·8674	79	82·8394	99	103·8114
20	20·9720	40	41·9440	60	62·9160	80	83·8880	100	104·8600

S. U.	B. A. U.	S. U.	B. A. U.	S. U.	B. A. U.	S. U.	B. A. U.	S. U.	B. A. U.
1	0·9537	21	20·0267	41	39·0998	61	58·1728	81	77·2459
2	1·9073	22	20·9804	42	40·0534	62	59·1265	82	78·1995
3	2·8610	23	21·9340	43	41·0071	63	60·0801	83	79·1532
4	3·8146	24	22·8877	44	41·9607	64	61·0338	84	80·1069
5	4·7683	25	23·8413	45	42·9144	65	61·9874	85	81·0605
6	5·7219	26	24·7950	46	43·8680	66	62·9411	86	82·0142
7	6·6756	27	25·7486	47	44·8217	67	63·8947	87	82·9678
8	7·6292	28	26·7023	48	45·7753	68	64·8484	88	83 9215
9	8·5829	29	27·6559	49	46·7290	69	65·8021	89	84·8751
10	9·5365	30	28·6096	50	47·6826	70	66·7557	90	85·8288
11	10·4902	31	29·5632	51	48·6363	71	67·7094	91	86·7824
12	11·4438	32	30·5169	52	49·5800	72	68·6629	92	87·7361
13	12·3975	33	31·4705	53	50·5436	73	69·6167	93	88·6897
14	13·3511	34	32·4242	54	51·4973	74	70 5703	94	89·6434
15	14·3048	35	33·3779	55	52·4509	75	71·5240	95	90·5970
16	15·2584	36	34·3315	56	53·4046	76	72·4776	96	91·5507
17	16·2121	37	35·2852	57	54·3582	77	73·4313	97	92·5043
18	17·1658	38	36·2388	58	55·3119	78	74·3849	98	93·4580
19	18·1194	39	37·1925	59	56·2655	79	75·3386	99	94·4117
20	19·0731	40	38·1461	60	57·2192	80	76·2942	100	95·3655

APPENDIX IV.

ON THE RECORDING OF REGULAR TESTS.

I. *Diary of Tests.*—A book should be kept on the Testing Table in which *all* tests, of whatever kind, should be fully entered as soon as made. From the rough entries in this book the Regular Tests will be computed, in accordance with the rules laid down in Appendix III., and the results will then be entered in the weekly Test Sheet.

II. *Test Sheet.*—A sufficient supply of loose Test Sheets should invariably be kept in stock in each Testing Station. A half-size Test Sheet is also issued for use, in case the number of Tests to be entered is small.

A sample Test Sheet, filled in from tests made in the Jabalpur Office, is annexed for guidance. The following are the chief points to be noticed in connection with the headings :—

No. of Test. This column contains consecutive numbers, either for one month or for the whole year; and each separate test made, no matter of what nature or for what purpose, is to be considered as *one* test, and is to be designated invariably by a consecutive number.

Date, Day, Hour Minute. This column does not require any explanation.

Battery. E. and *f*. E is the electromotive force of the testing battery as compared with that of the standard cell, while f is the total resistance of the testing battery. The methods to be employed in determining E and f depend entirely on the peculiar instruments available in the office. (See Appendix III., Part I., and Section I., Part III.)

If the constants of the testing battery are taken once a week, it will be quite sufficient.

Weather. See Appendix VI.

Temperature. See Appendix VI.

Name of station. In this column, in addition to the Code name of the distant station, the traffic number of the wire under test must be given.

Relay. The resistance of the relay through which the circuit test is made is given by the distant station in acknowledgment of the order "*Circuit:*" see Appendix II. The resistance of all relays issued from store are now reduced to 80° Fahr., and marked on the boards. If no temperature is entered, it will therefore be understood that the relay resistance is marked at 80° Fahr.

Weather. See Appendix VI. The state of the weather is given by the distant station in acknowledgment of the order "*Conduction ten minutes:*" see Appendix II.

Temperature. See Appendix VI. The temperature is given by the distant station in acknowledgment of the order "*Insulation ten minutes:*" see Appendix II.

Total length in miles: n. Reduced length in miles: m. Superintendents must furnish the Superintendent Electrician with tables giving the values of n and m for all the sections in their divisions; and any changes made should invariably be intimated to the Testing Officer concerned, and to the Superintendent Electrician.

See Note B, Appendix III.

A map, or its equivalent, should be kept in the Testing Office, showing the order and length of the different gauges on each line, and also the special features of the country the line traverses. Such a map will greatly facilitate the drawing of true conclusions with respect to any irregularity observed in the condition of the line.

Branch Resistances. In this column the branch resistances $\frac{b}{a}$ of the Bridge are to be inserted. (See fig. 1, Part I.) In case, however, of a differential galvanometer being employed for testing, the shunt used with one coil or the other should be inserted in this column.

Resistance unplugged to obtain balance. w' is the resistance actually unplugged in the comparison box to obtain balance when measuring with a positive current or copper pole of the testing battery to line; and w'' is the resistance unplugged when measuring with a negative current or zinc pole of the testing battery to line.

The tester should always verify the correctness of the arrangement, in so far that he is really sure that he measures with positive current or copper pole to line, when his commutator indicates this, and *vice versâ*.

Natural current. In this column the deflection is to be recorded which the line gives when put direct to earth through the testing galvanometer. See Preliminary § ii., Part II.

Measured values. See Preliminary § iii., Part II.; and Appendix III.

Corrected values. See Para. VI., Section I., Part II.; and Appendix III. As already stated, these values will coincide with the measured values if the line under test has a sufficiently high insulation, and then the measured values can be simply transferred.

If, however, the line under test has an insulation so low that the conduction resistance cannot be neglected against it, these values must be calculated by the proper formulæ.

Natural current. See Para. VII., Section I., and Para. IV., Section II., Part I.; and Appendix III. In this column are to be noted the direction (+ or −) and magnitude (when great) of the electromotive force of the current in the line which produces the difference between the positive and negative interests. It is expressed in terms of that of a Minotto element.

Relay. The column $W - w$ is always to be filled in. The column $\frac{I(W - w)}{I - W}$ need only be filled in when formulæ (17) and (18) are employed for correcting the measured values. The column r must be filled in when the measured values are corrected by formulæ (14) and (15).

$\frac{l}{L}$ See Appendix III. This column must invariably be filled in whenever the measured values require correction. On a line uniform in conduction and insulation $\frac{l}{L} = 0{\cdot}5$.

Remarks. Any remarks that the Testing Officer may think it necessary to make in connection with the regular tests should be entered in this column.

III. *Register of Tests.*—In every Testing Office a "Register of Tests" is to be kept for each line terminating in the office. The Register is a book containing 100 of the Test Sheets. When the tests of the week have been computed and entered in the Test Sheet as above, in their consecutive order, then the tests are to be copied into the Registers of the several lines tested; and the Test Sheet is to be sent on at the end of the week, *in original*, to the Superintendent of the Division in which the lines are situated. Each Test Sheet should contain only the tests of lines in one and the same Division. If the lines of more than one Division are tested from the same office, then a separate Test Sheet must be made out for each Division, and forwarded to the Superintendent concerned.

Arranged under the heads of the several sections tested, the Test Registers will present all the data necessary for the accurate Localisation of Faults.

IV. *Abstract of Tests.*—The form known as the "Abstract of Tests" is for use in the Superintendent's office.[1] A sheet of Abstracts is to be kept in the Superintendent's office for each line the tests of which are received by him.

On the receipt of a Test Sheet, the Superintendent, having scrutinised the results and checked the calculations when necessary, will, in the first place, at once enter the results in the "Abstract of Tests," under the heads of the several sections of wire tested, and then forward the original to the Superintendent Electrician.[2]

It is not intended that Superintendents should re-calculate every test themselves; but they should occasionally check calculations taken at hazard from the Test Sheets of an office, in order to exercise the necessary control over the work, and the number of these checks should depend entirely on the degree of confidence they have in the Testing Officer.

Superintendents, by examining the Test Sheets of their Divisions, will be able to exercise a most efficient control over the manner of their preparation; and by pointing out any mistakes that occur in the selection of formulæ, and by insisting on accuracy of calculation, will reduce the labour of checking the sheets to a minimum.

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[1] For sample "Abstracts," see end of Appendix V.

[2] The Test Sheets should not, as a rule, be retained more than three days in the Superintendent's office.

The labour of calculation, however, should fall on the Testing Officer, and not on the Superintendent. All the clerical work that has to be done by the latter is (subject to occasional control calculations) to enter the results in the "Abstract of Tests."

In the "Abstract of Tests" Superintendents will continually have before them a complete record of the state of their lines; and by at once taking remedial measures when they detect any irregularity in their behaviour, they will be able to maintain them in their normal condition. Thus testing becomes a most powerful instrument in the hands of Superintendents to aid them in the administration of their Divisions; and the labour involved is, or should be, exceedingly slight, and out of all proportion to the immense assistance it must prove to the Superintendents themselves towards the successful management of their Divisions.

TEST SHEET OF THE JABALPUR OFFICE

No. of Test.	DATE.			FROM				TO				DIMENSIONS OF WIRE.		BRANCH RESISTANCES.	RESISTANCE UNPLUGGED TO OBTAIN BALANCE.		NATURAL CURRENT.
1876.	Day.	Hour.	Min.	BATTERY. E	BATTERY. f	Weather.	Temperature $\frac{wet}{dry}$ bulb.	Name of Station.	Relay marked.	Weather.	Temperature $\frac{wet}{dry}$ bulb.	Total length in miles. n	Reduced length in miles. m	$\frac{b}{a}$	w' +	w'' −	Deflection $\frac{\text{before}}{\text{after}}$ Test.
1023	19th	20	24	37	512	R/F	$\frac{73}{82}$	Ad. 1	1411	F	$\frac{82}{91}$	229	487	$\frac{1000}{1000}$	3700	3660	$\frac{35}{40}$ R
1024														$\frac{1000}{1000}$	2330	2270	$\frac{40}{20}$ L
1025														$\frac{1000}{10}$	4000	1000	
1026	19th	20	35	37	512	R/F	$\frac{73}{82}$	Ad. 2	2888	F	$\frac{82}{91}$	229	321	$\frac{1000}{1000}$	4350	4230	$\frac{18}{10}$ R
1027														$\frac{1000}{1000}$	1600	1530	$\frac{40}{45}$ R
1028														$\frac{1000}{100}$	5500	2100	
1029	19th	20	45	37	512	R/F	$\frac{73}{82}$	Ad. 4	2128	F	$\frac{82}{91}$	229	487	$\frac{1000}{1000}$	4470	4300	$\frac{12}{18}$ R
1030														$\frac{1000}{1000}$	2330	2300	$\frac{13}{0}$ R
1031														$\frac{1000}{10}$	1200	900	
1032	19th	20	55	37	512	R/F	$\frac{73}{82}$	Ad. 5	1434	F	$\frac{82}{91}$	229	479	$\frac{1000}{1000}$	3240	3100	$\frac{15}{22}$ R
1033														$\frac{1000}{1000}$	2120	2200	$\frac{45}{42}$ L
1034														$\frac{1000}{100}$	1300	1000	
1035	21st	20	15	37	512	R	$\frac{74}{77}$	Sau.	430	R	$\frac{76}{78}$	133	277	$\frac{1000}{1000}$	1620	1680	$\frac{25}{20}$ L
1036														$\frac{1000}{1000}$	1294	1280	$\frac{10}{20}$ R
1037														$\frac{1000}{100}$	1100	1400	
1038	21st	21	3	37	512	R	$\frac{74}{77}$	Kwa. 2	745	R/C	$\frac{78}{80}$	264	550	$\frac{1000}{1000}$	2040	2160	$\frac{44}{44}$ L
1039														$\frac{1000}{1000}$	1570	1620	$\frac{24}{15}$ L
1040														$\frac{1000}{1000}$	5000	5200	
1041	21st	21	15	37	512	R	$\frac{74}{77}$	Kwa. 1	745	R/C	$\frac{78}{80}$	264	367	$\frac{1000}{1000}$	2900	3070	$\frac{80}{45}$ L
1842														$\frac{1000}{1000}$	2450	2520	$\frac{50}{30}$ L
4310														$\frac{1000}{1000}$	7000	8500	

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* In order to fit the book this table has been reduced

FOR THE WEEK ENDING 24TH JULY 1875.*

CIRCUIT.	MEASURED VALUES.				CORRECTED VALUES.				Natural current.	RELAY.				REMARKS.
	CONDUCTION.		INSULATION.		CONDUCTION.		INSULATION.							
	Absolute.	Per mile.	Absolute.	Per mile.	Absolute.	Per mile.	Absolute.	Per mile.		$W-w$	$\frac{I(W-w)}{I-W}$	Real at Temperature of Test.	$\frac{l}{L}$	
W	w	$w \div m$	I	$I \times n$	L	$L-m$	i	$i \times n$	$\pm e$			r		
				megohms				megohms						
3680	2250	4·63	325000	74·7	2252	4·63	323270	74·4	—	1430		1441	0·768	
4290	1565	4·88	46500	10·7	1568	4·94	45306	10·6	—	2725		2949	0·761	
4385	2315	4·77	112500	25·8	2339	4·82	111828	25·6	—	2070		2173	0·287	
3170	2160	4·51	12250	2·82	2363	4·93	11524	2·64	—	1010		1464	0·307	
1650	1287	4·64	11750	1·56	1335	4·81	11162	1·49	+	363		428	0·440	
2100	1595	4·35	5050	1·33	1646	4·50	3878	1·03	+	505		745	0·712	
2985	2485	4·53	7375	1·95	2604	4·75	5656	1·50	+	500		745	0·66	

in size. Actually, the table has about four times the area.

APPENDIX V.

ON THE COMPILATION OF REGULAR TESTS.

I. Yearly, on the 1st of January,[1] each Superintendent will prepare, for submission to the Director-General, a statement (to be compiled directly from the "Abstract of Tests") giving the maximum, average, and minimum insulation and conduction for each section tested in his Division during the preceding year.

It should reach the Director-General's office not later than the 1st February.

Superintendents should note briefly all changes made in the lines; *e.g.*, if the detector has been used, how many insulators were found faulty by the hand, and how many by the tongue; all alterations in length or gauge of the wire; or, if no changes have taken place during the year, this should be stated; and generally all facts necessary to be considered with the electrical tests to admit of just inferences.

II. When called upon by the Director-General (but not otherwise), Superintendents will submit in detail, through the Superintendent Electrician, the compilation for certain periods of the tests of any lines that appear to require special attention.

That full value may be derived from the Superintendent's "General Results and Conclusions," these will be based, not on tests of periods arbitrarily chosen, but on those of periods corresponding to monsoons and other climatic changes, since the real criterion of a line's insulation is its behaviour under the most adverse conditions.

For instance, the tests taken from June to September will, in Northern India, generally comprise the whole of the wet weather observations; but the seasons as they occur should be followed, and in the event of an unusually early or protracted monsoon, the period selected should be varied to correspond.

The special forms employed in the detailed compilation of the tests of particular lines are appended. The "Abstract of Tests" forms the basis of the compilation, and the original abstracts (of which duplicate copies need not be made), from which the results have been drawn, should invariably accompany the compilation.

The "Monthly Averages" (for so many months as the compilation period may include) should be first filled up. No difficulty will be experienced in doing this.

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[1] Commencing from January 1, 1877.

With regard to the "General Results and Conclusions," it should be understood that, as in the Annual Statement, the maxima and minima insulation and conduction referred to are the *absolute* maxima and minima of the period, and should be taken directly from the Abstract of Tests; and further, that the average is the average of the results of all the tests made (not the average of the monthly averages), and must, therefore, also be computed directly from the Abstract of Tests.

The Director-General will return the detailed compilations with such orders as he may consider it necessary to pass on the subject to the Divisional Superintendent, who will file them in his Office, where they will form a most valuable local record.

ANNUAL STATEMENT.

YEAR 187 .

Line No. 3, from X to Y. *Miles,* 302. *Direction, S.W. to N.E.*

Gauges of wire,	1 mile No. 16 I. W. G. 300 miles No. 24 I. W. G.	Cables,	Length, 1 mile. No. 2.	Insulators,	Pattern. Excentric catch. Porcelain. "A."

		Date.	Hour.	Temperature.	Weather
Average insulation per mile = 37 megohms from 50 tests at 77° Fahr. 82° ,,	Max. = 112	May 3d	10	76° Fahr. 95° ,,	F.
	Min. = 2·5	Aug. 7th	7	80° ,, 81° ,,	R/O.
Average conduction per mile = 5·07 ohms from 50 tests at 82° ,,	Max. = 5·5	May 3d	10	95° ,,	F.
	Min. = 4·7	Dec. 29th	8	68° ,,	F.

Average position of Resultant Fault $\frac{l}{L}$ = 0·47 from 50 tests.

NATURAL CURRENTS.

+		0	–	
Number.	Maximum.	Number.	Number.	Maximum.
31	2·75	2	14	1·43

....

Superintendent of Telegraphs,

January 187 . ... *Division.*

GENERAL RESULTS AND CONCLUSIONS.

Line No. 7, from Madras to Bellary, via *rail, miles* 310. *September to December* 1875.

		Date.	Hour.	Temperature.	Weather.
Insulation : average = 1·76 from 18 tests at $\frac{72^\circ}{78^\circ}$ Fahr. ,,	Max. = 3·31	3d December,	10	$\frac{72^\circ}{78^\circ}$ Fahr. ,,	C to F.
	Min. = 0·62	15th December,	10	$\frac{74^\circ}{79^\circ}$,, ,,	R/O to C/F.
Conduction : average = 5·06 from 18 tests at 78° ,,	Max. = 5·91	21st September,	10	83° ,,	C to O/F.
	Min. = 4·01	15th December,	10	79° ,,	R/O to C/F.

Natural Currents : average = + ...from 12 tests; − ....from 6 tests. Range = + 3·04 to − ....

Localised Faults : Nil.
- Dead Earth ... ...
- Partial Earth ... ...
- Contacts ... ...
- Discontinuity
  - Total ...
  - Partial ...

Conclusions and Suggestions by the Superintendent.

The insulation of this line cannot be considered as sufficiently good; and the tests have consequently been compiled in detail for the information of the Director-General, with reference to his No. 9999 C., dated the 7th February 1876. Ever since the construction of the railway line, the insulation of this wire has always been far smaller than that of its fellow wire on the same posts, No. 6, supported on Prussian pattern insulators. Since the issue of the Superintendent Electrician's Reports on the tests of this line for the periods $\frac{\text{January}}{\text{August}}$ and $\frac{\text{September}}{\text{December}}$ 1873, the insulators on the Section Madras to Arconum have been tested with the Detector (February-March 1875); but no sensible improvement in insulation has taken place, although a considerable percentage of insulators were rejected. This indicates clearly that defective insulators still exist between Arconum and Bellary.

The conduction is right. The maximum is probably due to an observation error.

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Superintendent of Telegraphs,
Madras Division.

MONTHLY AVERAGES.

September to December 1875. *Madras to Bellary. No. 7 Line.*

September	Corrected Insulation per mile (mean of 5 tests)	2·23 megohms	Weather C to F/O.
	„ Conduction „ („ „)	2·274 ohms	Temp.: dry bulb, about 81°; wet bulb, about 74° F.
	Electromotive force in the line („ „)	+ 3 – 2	All tests made between 7 and 11 hours.
October	Corrected Insulation per mile (mean of 4 tests)	1·46 megohms	Weather R/C to C.
	„ Conduction „ („ „)	4·9 ohms	Temp.: dry bulb, about 79°; wet bulb, about 75° F.
	Electromotive force in the line („ „)	+ 2 – 2	All tests made between 7 and 11 hours.
November	Corrected Insulation per mile (mean of 4 tests)	1·707 megohms	Weather R/C to F.
	„ Conduction „ („ „)	5·065 ohms	Temp.: dry bulb, about 78°; wet bulb, about 70 F.
	Electromotive force in the line („ „)	+ 3 – 1	All tests made between 7 and 11 hours.
December	Corrected Insulation per mile (mean of 5 tests)	1·65 megohms	Weather R/C to C/F.
	„ Conduction „ („ „)	4·96 ohms	Temp.: dry bulb, about 75°; wet bulb, about 70° F.
	Electromotive force in the line („ „)	+ 4 + 1	All tests made between 8 and 11 hours.

ABSTRACT OF TESTS.

Length, 310 Miles.
Gauges, 1·25 of No. 12, and 308·75 of No. 24.

From Madras to Bellary.
Line No. 7; Direction of Line, S.E. to N.W.

Description of Insulators. { Pattern Mixed. Porcelain.

DATE.		WEATHER.		TEMPERATURE $\frac{wet}{dry}$ bulb.		INSULATION.		CONDUCTION.		RELAY.			$\frac{l}{L}$	Electromotive force in line.	REMARKS.
Day.	Hour.	From	To	From	To	Measured absolute in ohms.	Corrected per mile in megohms.	Measured absolute in ohms.	Corrected per mile in ohms.	Measured.	Corrected.	Real.[1]			
1	8	C/O	F	77 83	71 76	8075	2·1	2735	4·91	985	...	1914	0·417	+	
8	10	C	F	77 86	72 80	12100	3·3	3060	5·37	1200	...	1982	0·375	−	
15	8	C	F	75 82	70 76	9950	2·7	2885	5·21	1065	...	1944	0·349	+	
21	10	C	O/F	80 83	71 82	6960	1·94	2800	5·91	725	...	1967	0·214	−	
29	8	C	O	78 83	71 75	5000	1·14	2575	4·97	625	...	1941	0·408	+	
NO FAULTS.															
Mean.		C	F	77 83	71 78	8415	2·336	2811	5·274	Month, September 1875.					

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[1] At Temperature of Test.

ABSTRACT OF TESTS.

Length, 310 Miles.
Gauges, 1·25 of No. 12, and 308·75 of No. 24.

From Madras to Bellary.
Line No. 7; Direction of Line, S.E. to N.W.

Description of Insulators. { Pattern Mixed. Porcelain.

DATE.		WEATHER.		TEMPERATURE. $\frac{wet}{dry}$ bulb.		INSULATION.		CONDUCTION.		RELAY.			$\frac{l}{L}$	Electromotive force in line.	REMARKS.
Day.	Hour.	From	To	From	To	Measured absolute in ohms.	Corrected per mile in megohms.	Measured absolute in ohms.	Corrected per mile in ohms.	Measured.	Corrected.	Real.[1]			
6	10	R/C	O/C	82 84	73 79	3275	0·75	2075	5·08	345	...	1956	0·261	+	
14	8	C	F	76 79	63 73	9300	2·5	2795	4·75	930	...	1653	0·403	+	
22	11	R/C	R/C	78 82	75 80	5500	1·3	2800	5·59	660	...	1676	0·359	–	
30	7	R/C	F	79 82	72 75	5625	2·29	2950	4·46	433	867	1660	0·001	–	
NO FAULTS.															
Mean.		R/C	C	79 82	71 77	4800	1·46	2655	4·97	Month, October 1875.					

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[1] At Temperature at Test.

ABSTRACT OF TESTS.

Length, 310 Miles.
Gauges, 1·25 of No. 12, and 308·75 of No. 24.

From Madras to Bellary.
Line No. 7 ; Direction of Line, S.E. to N.W.

Description of Insulators. {Pattern Mixed. Porcelain.

DATE.		WEATHER.		TEMPERATURE. $\frac{wet}{dry}$ bulb.		INSULATION.		CONDUCTION.		RELAY.			$\frac{l}{L}$	Electromotive force in line.	REMARKS.
Day.	Hour.	From	To	From	To	Measured absolute in ohms.	Corrected per mile in megohms.	Measured absolute in ohms.	Corrected per mile in ohms.	Measured.	Corrected.	Real.[1]			
4	10	F	F	67 82	60 75	10850	2·91	2915	5·31	1010	...	1660	0·132	÷	
12	7	R/O	F	78 81	70 74	6500	1·79	2620	5·35	755	...	1656	0·201	+	
17	10	R/C	F	77 80	69 77	6850	1·65	2685	4·65	550	1054	1666	0·03	+	
24	8	R/C	F	77 78	66 71	5700	1·48	2475	4·95	610	...	1647	0·29	–	
NO FAULTS.															
Mean.		R/C	F	77 80	66 67	7750	1·707	2673	5·065	Month, November 1875.					

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[1] At temperature of test.

ABSTRACT OF TESTS.

Length, 310 Miles.
Gauges, 1·25 of No. 12, and 308·75
of No. 24.

From Madras to Bellary.
Line No. 7; Direction of Line, S.E. to N.W.

Description of Insulators. { Pattern Mixed. Porcelain.

DATE.		WEATHER.		TEMPERATURE. $\frac{wet}{dry}$ bulb.		INSULATION.		CONDUCTION.		RELAY.			$\frac{l}{L}$	Electromotive force in line.	REMARKS.
Day.	Hour.	From	To	From	To	Measured absolute in ohms.	Corrected per mile in megohms	Measured absolute in ohms.	Corrected per mile in ohms.	Measured.	Corrected.	Real.[1]			
3	10	C	F	79 81	67 64	11850	3·34	2857	5·05	1023		1656	0·336	+	
8	8	R/C	O	77 79	68 84	5450	1·5	2435	5·57	530		1656	0·176	+	
15	10	R/O	C/F	78 80	70 77	3445	0·62	2160	4·01	450		1666	0·569	+	
22	8	L	F	70 73	60 68	3860	0·90	2215	4·90	400		1637	0·305	–	
30	10	F	F	73 79	62 74	7450	1·91	2704	4·92	815		1656	0·414	3·04	
NO FAULTS.															
Mean.		R/O	F	75 78	65 75	6441	1·654	2474	4·906	Month, December 1875.					

[1] At temperature of test.

APPENDIX VI.

WEATHER OBSERVATIONS.

I. The hygrometer must be placed in such a position that the dry bulb thermometer will assume the temperature of the outside air. It must not be placed in a confined room, but in a position such that there is a free circulation of air. At the same time, care must be taken that it is not exposed either to the direct or reflected rays of the sun, or to radiation from heated masonry or buildings, or from the ground. It must not be placed where there is a strong draught of air, or else the wet bulb readings will be erroneously low. The piece of muslin or cambric on the wet bulb requires frequent changing, as it rapidly becomes dirty and changes its character. It must not be of such a texture that it will become super-saturated with water, as the air will be unable to take up the just proportion of moisture, and the wet bulb thermometer will give readings erroneously high. Any kind of material with "size" on it should be first soaked in fresh water to remove it before use. The water used in the small glass reservoir must be clean, "soft" (rain) water, and must be frequently changed. Inspecting officers should make it a point to see that the hygrometers are properly exposed and looked after.

II. Testing officers must bear in mind that the insulation of a line at any time depends to a great extent on the previous history of the line. If, therefore, in any case, the circumstances to which a line has been subjected, *immediately previous to the time of testing it*, have been exceptional, or *different from those under which the test is made*, mention should be made of them in the Test Sheet. For example, it may be bright and sunny at the actual time of making a test, but it may have rained heavily the previous day, or even a few hours before. Or, again, it may be dark, cloudy, even raining, at the actual time of making a test, but it may have been dry weather for months previously, and even up to within a few hours of the test. When, therefore, in future, an entry is made in the Test Sheet *only* of the weather at the actual time of making the test, it will be understood that the weather mentioned not only existed at the time of testing, but that it had existed for *at least* 24 hours previously. Thus the simple entry "*fair*" will be held to imply that not only was the weather fair at the time of making the test, but that it had been so for *at least* the preceding 24 hours. On the other hand, in every case that the weather has changed during the preceding 24 hours, the *previous* weather must be shown as well as the *actual* weather. Further, in every instance that a high wind is blowing at the time of making the test, mention should be made of the circumstance, for it has been found that the insulation may be affected by it.

III. For the future, in signalling to the Testing Station the state of the weather, the following code will be observed, and, as a rule, no other signals are to be employed :—

F *for* "fair." This means that the sun is shining (if the test is made by day), and that the sky is serene and clear.

C *for* "cloudy." This means that the sun is shining (if the test is made by day), but that clouds are visible in the sky.

O *for* "overcast." This means that the sky is overcast by clouds, and that (if the test is made by day) the sun is obscured.

G *for* "fog."

R *for* "raining."[1]

D *for* "damp." This means that the surfaces of exposed bodies, such as the insulators, are covered with moisture—*e.g.*, from dew, fog, or recently fallen rain.

W *for* "high wind."

When reference is made to the weather *previous* to the time of making the test, the code signal indicative of the *previous* weather will be sent first; the signal indicative of the *actual* weather (at the time of making the test) will be sent last; and the two signals will be separated by the code signal **P** (perpendicular bar). Thus, suppose the weather previous to the test had been *raining*, and that at the actual time of the test was *cloudy*, with a *high wind*, then this would be represented by **R | C W.**

For the sake of brevity and precision, the entries in the Test Sheets, too, will be made in the code (by means of the appropriate letters), care being taken to always insert, when necessary, the perpendicular bar, so as to clearly distinguish the *previous* from the *actual* weather.

Particular attention is directed to the distinction between **C** and **O.** In the former case the sun is shining on the wire and insulators, but not in the latter case.

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[1] *Raining*, not *rainy*, which is a meaningless entry.

SECTION II.

FAULT TESTING.

I. *Fault Testing* has for its object the localisation of all defective points in a line, including not only those which actually prevent or interfere with communication, but also those which may ultimately do so if neglected.

II. *Classification of Faults.*—Faults will be considered under three heads, *viz.*:—Faults of Conduction, Faults of Insulation, and Faults of Interference of Circuits—or, as they are technically called, "Disconnections," "Earths," and "Contacts."

Disconnections may arise from a variety of causes, such as breaking of the line wire, instrument wire fused by lightning, plug left out of switch, dirty contacts, bad joints, loose shackles, defective earth-plates, &c.; and, generally, from any cause which *introduces a foreign resistance into the circuit.*

Earths may be caused by the contact of the line wire with trees, jungle, houses, railway signal-posts, &c., or by the wire falling from the insulators and touching the posts, ground, brackets, stays, &c., or by the insulator hood touching the bracket, or by defective insulators, or by the fusing together of the plates of a lightning protector; and, generally, is due to any cause which *diminishes the insulation resistance of the line.*

Contacts may occur through line wires twisting together, or hooking together at joints, or through waste, kite-strings, bits of wire, dead snakes, fish, or offal dropped by birds, &c., lying across the wires, or through birds making nests of conducting materials between the wires,[1] or through bad earth-plates, or may be produced on a line having wooden supports by damp rainy weather; and, generally, is due to any cause which *diminishes the insulation of the lines with respect to one another.*

It may sometimes happen that two or all three of these classes of faults occur together. Especially is this the case with *disconnection* and *earth;* and, further, the wire in which these two faults exist may also have come into *contact* with one or more of the other wires. In such cases great care is required in order to arrive at correct results.

III. *To localize a disconnection.*—Disconnections are either "total" or "partial." In the first case two consecutive points of the line are separated by a resistance indefinitely large as compared with the normal resistance of the circuit. In the second case two consecutive points of the line are separated by a resistance of finite magnitude as compared with the normal resistance of the circuit. In other words, in the former case the breach of continuity is practically complete, and communication is entirely prevented; while in the latter case communication is only interfered with, more or less seriously according to the resistance offered by the disconnection, to the E. M. F. of the signalling battery, and to the sensitiveness of the receiving instrument.

§ 1. Total disconnection.—There are two distinct methods of localising these faults, *viz.;* by an "insulation" test and by a "capacity" test.

The first method assumes that the insulation of the line is uniform throughout, and that, therefore, provided the wire is perfectly insulated[2] at the place of disconnection, the distance of the fault from the testing station is to the whole length of the line in the ratio of the absolute insulation of the whole line (known from the regular tests) to the absolute insulation up to the fault (found by the fault test).

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[1] The Calcutta crows frequently construct their nests of the old wire off soda-water bottles.—Proceedings of the Asiatic Society of Bengal, 1874, p. 74.

[2] "Disconnections" that are not insulated are treated of under the head of "Earths;" *e.g.*, when the line wire breaks and rests on the ground, making Earth.

Thus, let n be the distance of the fault, N the number of miles the line is in length, I the absolute insulation of the broken line, and i the absolute insulation of the whole line before the interruption occurred (to be taken from the Register of Tests—a test if possible being selected which was made during similar weather, and at the same hour of the day as that at which the fault test has been made), then

$$\frac{N}{n}=\frac{i}{I}$$

$$\therefore \quad n=\frac{i}{I}N \qquad \dots \quad \dots \quad \dots \quad (28)$$

The insulation of any line, however, is a very variable quantity,[1] whether owing to climatic or other influences, and therefore the above formula, in which it is assumed that the insulation of the line has not altered from the time of making the "regular" test to the time of making the "fault" test, in most cases is not to be depended on. The result obtained should always be controlled by the much more reliable "capacity" test.

The method of testing by "capacity" assumes that the inductive capacity of the line is uniform throughout its length, and that, therefore, provided the wire is perfectly insulated at the place of disconnection, the distance of the fault from the testing station is to the whole length of the line in the ratio of the absolute capacity up to the fault (found by the fault test) to the absolute capacity of the whole line (known from previous tests).

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[1] Suppose that there is at least a second perfect wire running parallel with the defective one, as is generally the case in India, and suppose that the ratio of the insulation of the two wires when both are in working order is known and is fairly constant, then measure the insulation of the perfect wire at the time of localising the fault in the other, and use this value, multiplied by the coefficient expressing the known ratio, for i, which obviously will be far more probably correct than the value of i taken from the regular tests of the defective line at a previous period.

Thus, let n be the distance of the fault, N the whole length of the line, c the absolute capacity of the broken line, and C the absolute capacity of the whole line, then

$$\frac{n}{N}=\frac{c}{C}$$

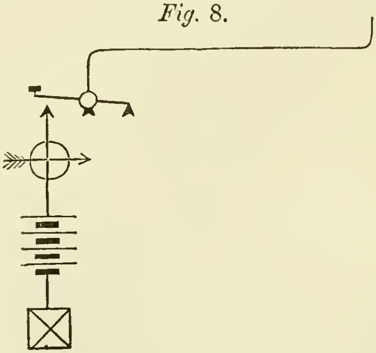
$$\therefore \quad n=\frac{c}{C}N$$

It only remains to explain how c and C are to be measured.

The capacity of a line is proportional to the quantity of its charge with a given electromotive force; which can be found either by measuring the transient current due to "charge," or by measuring the transient current due to "discharge."

To measure the capacity *by charge*, insulate the distant end of the line, and insert a key and galvanometer

Fig. 8.



between the near end and one pole of a battery, the other pole of which is to earth.

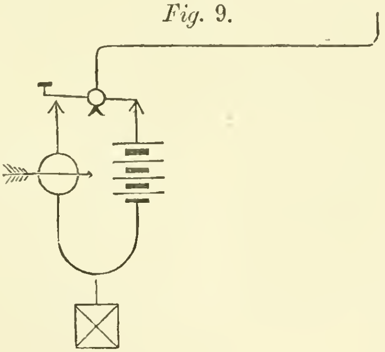
Make momentary contact, and observe a the throw of the needle due to the transient current; then we have[1]

$$q = k \sin \frac{a}{2}$$

where q is the total quantity of electricity that has passed through the galvanometer during the time of contact, and k is a constant depending on the nature of the instrument, &c. No greater battery power should be used than is required to get a readable deflection with the galvanometer employed. It is always better to use the galvanometer without shunting it, and to reduce the electromotive force in case the deflection should prove too large.[2]

To measure the capacity *by discharge*, insulate the distant end of the line, and connect the near end to the middle contact of a key. Between the back contact and the earth insert the battery; and between the front contact and the earth insert the galvanometer.

Fig. 9.



Charge the line, by leaving the key in its position of repose for a certain time—sufficiently long to permit of the line attaining its maximum charge for the given E. M. F. At the end of this time discharge the line immediately, by a momentary contact, through the galvanometer, and note the deflection a of the needle; then, obviously, we have the same formula as before

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[1] For a proof of this see Clerk Maxwell's "Electricity and Magnetism," vol. ii. p. 346, par. 748.

[2] In order to diminish the strength of the damping force due to the currents induced in the galvanometer coils by the moving magnet.

$$q = k \sin \frac{a}{2}$$

Now, if a be the deflection observed when measuring the capacity of the whole line (known from previous tests), and a' the deflection when measuring the capacity of the line up to the fault; then, by either method, we have[1]

$$n = \frac{c}{C} N = \frac{E}{E'} \cdot \frac{q}{Q} N = \frac{E\, k' \sin \frac{a'}{2}}{E'\, k \sin \frac{a}{2}} N \qquad \ldots \qquad (29)$$

where E is the E. M. F. of the testing battery when taking the charge or discharge of the whole line, and k is the constant of the instrument at that time; E' is the E. M. F. of the testing battery when taking the charge or discharge of the broken line, and k' is the constant of the instrument at that time.

From the two results obtained by the insulation and capacity tests the most probable n should be computed. Say the weight attached to the localisation by the insulation test is represented by the coefficient α; and to the

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[1] We have

$$Q = C\, E$$
$$q = c\, E'$$
$$\therefore \quad \frac{c}{C} = \frac{E}{E'} \cdot \frac{q}{Q}$$

localization by the capacity test by the coefficient β; then, the most probable n would be:

$$n = \left(\alpha\frac{i}{I} + \beta\frac{c}{C}\right)\frac{N}{\alpha+\beta} \quad \ldots \quad \ldots \quad (30)$$

The coefficients α and β are absolute numbers ranging between 0 and $+\infty$, whose special values in each particular case must be found by considerations depending on local circumstances, and arrived at by reasoning from probability. Generally, a near disconnection will be characterized by high insulation and low capacity; and a distant disconnection by low insulation and high capacity.

§ 2. Partial disconnection.—The resistance of partial disconnections is generally extremely unstable, and often varies at short intervals of time between 0 and ∞. It is obvious, therefore, that the very nature of these faults is such as to throw considerable difficulty in the way of their accurate localization, and they may consequently at times cause great trouble. But, even when the partial disconnection is of a more stable character, its localization by a direct method is still a matter of difficulty, on account of its requiring greater accuracy of experiment than can usually be attained in a Telegraph office with lines of inconstant electrical condition. In such a case, therefore, it is better to have recourse to an indirect method.

The following is a method of localizing an *intermittent* partial discontinuity on a *single* line:[1]—The line is to be connected permanently through a fixed resistance z to earth, the best point to commence with being the middle of the line. The resistance z, acting as a fault, should be made as small as practicable, but sufficiently large not to interfere seriously with the working—say, for instance, $z=L$, the measured conduction resistance of the whole line when in its normal condition. Now measure from time to time the resistance offered by the line when insulated at the distant station. If the discontinuity offers such a high resistance that it prevents communication, the distant station will understand *e ra natâ* that it is to insulate. Say the resistance found is w, and l is the known conduction resistance of the line up to the point where the artificial fault has been placed, then either

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[1] There is only *one* line existing.

$$w = l+z$$

or

$$w > l+z$$

from which it is known in which of the two sections the disconnection is situated. Next, the constant resistance z, acting as a fault, is removed to the middle of the half which has been found to contain the disconnection; and so on, until the defective point is brought within sufficiently near limits to admit of its being discovered by close inspection, or of the joints being repaired, doubtful places looked to, &c. Of course, if the partial disconnection is of a *permanent* character, it is better to send out a man on the line, who connects the line to earth at different places, his movements being directed from the testing station. A partial disconnection occurring in one wire of a *multiple* line can be localized by "crossing" the defective wire with a good wire in different sections successively, and making the necessary tests to ascertain in which section the fault becomes transferred from the one circuit to the other.

IV. *The constant k.* We had

$$n = \frac{c}{C} \cdot N = \frac{E}{E'} \cdot \frac{k'}{k} \cdot \frac{\sin \frac{a'}{2}}{\sin \frac{a}{2}} \cdot N \quad \dots \quad \dots \quad (29)$$

Now in order to be able to calculate the distance n of the fault from the known length N of the line, in addition to a and a' (to be determined by experiment), we must also know the ratios $\frac{E}{E'}$ and $\frac{k'}{k}$.

The ratio $\frac{E}{E'}$ either may be calculated from the number of cells employed in the two observations, or may be found by a direct experimental comparison of the E. M. F. of the two batteries.

The ratio $\frac{k'}{k}$ still remains unknown. If, for instance, the two observations were taken at the same time with the same instrument, then $k'=k$ obviously; but, as the one observation may have been taken some time before the other, it would be erroneous to still assume the ratio to be unity, even although the same instrument have been employed, for k is a coefficient generally by no means constant with respect to time. In fact, we know that :—

$$k = 2\frac{HT}{G\pi} \qquad \dots \quad \dots \quad \dots \quad (31)$$

where H is the horizontal component of the earth's magnetic force at the place of observation (this for our purposes we may consider to be constant); G is a coefficient depending on the nature and special construction of the galvanometer (also constant with respect to time); and T is the time of a single vibration of the magnet. This quantity T is highly variable with respect to time, since sensitive testing galvanometers generally have astatic needles, the directive force acting on which is governed by a permanent magnet fixed in their neighbourhood. To eliminate, therefore, this source of variability in the coefficient k, when we make a "regular" test of the capacity of a line, we should note the number of oscillations executed by the magnet in a given time, and before making a "localization" test we should adjust the permanent directing magnet so as to obtain the same number of oscillations in the same time. The two observations will then be comparable.

All difficulty with regard to the constant k is removed in any office (such as an office in which duplex working has been introduced) where a condenser of known capacity is available. For, let S be the capacity in microfarads of the condenser available, in terms of which the capacity C of the line is to be measured, then as before

$$\frac{C}{S} = \frac{E}{E'} \cdot \frac{k'}{k} \cdot \frac{\sin\frac{a'}{2}}{\sin\frac{a}{2}}$$

but as the two observations are made at the same time, and with the same galvanometer[1]

$$k = k'$$

Whence $$C = \frac{E}{E'} \cdot \frac{\sin\frac{a'}{2}}{\sin\frac{a}{2}} \cdot S \text{ M. F.}$$

If at any time a disconnection should occur, we have only to compare in the same way the capacity of the defective line with the capacity of the condenser, in order to obtain its capacity c in microfarads. Then we have again—

$$n = \frac{c}{C} N$$

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[1] The condenser should first be tested, then the line, and finally the condenser again. If the first and last tests of the condenser agree, then the coefficient k will have remained constant throughout the experiment. Testing offices not supplied with a condenser may use the capacity of a short and well-insulated line as the standard of reference.

V. *Errors of the Method.*—The method of determining the capacity of a Telegraph line by observing the first throw of a galvanometer needle when either under the influence of charge or discharge, is correct only under the following circumstances:—

1. In order that the quantity of electricity transmitted be proportional to the sine of half the angle to which the needle is deflected, the current must last only a very small fraction of time, as compared with the period of vibration of the magnet.
2. The full charging-time of the line under test must fall within the time during which the contact either for charging or discharging is made.
3. The insulation of the line must be high, in order that the leakage current be an insignificant fraction of the transient current which measures the capacity.

The *first* condition we can fulfil in practice by making the time of contact small, as compared with the time of a single vibration of the needle, either by making the time the contact lasts in itself small, or better by employing a slow swinging galvanometer needle.

The *second* condition we can only fulfil when dealing with lines of short length, or more generally with a line of small absolute conduction resistance and small absolute capacity. We know that a Telegraph line, and especially a long submarine cable, takes a very perceptible time for charging and discharging itself to its full extent. Hence in such a case the quantity of electricity received or discharged within this short interval of time cannot represent the full quantity which the line can hold, and to which alone the capacity is proportional. But whatever the magnitude of this error may be, it will be clear that under all circumstances its influence must be such that the measured capacity is smaller than the real capacity; and further, that the longer the line is, the more the time of contact should be increased; and in order to fulfil also the first condition, the slower the galvanometer needle should swing.

Say that the measured capacity by charge is ρ', by discharge is ρ'', and the real capacity is ρ, then we have

$$\rho' = \rho - \Delta' \quad \text{charge test.}$$
$$\rho'' = \rho - \Delta'' \quad \text{discharge test.}$$
$$\therefore \qquad \rho = \frac{\rho' + \rho''}{2} + \frac{\Delta' + \Delta''}{2} = \frac{\rho' + \rho''}{2} + \Delta$$

where Δ' and Δ'' are the errors made. They both become zero for short lengths of cable, or overland lines under 200 miles in length. Further, for any given length of line they can be both reduced by lengthening the time during which the key contacts last, provided the time of vibration of the needle be proportionately increased.

The *third* condition it is not in our power to fulfil, for the leakage of a Telegraph line is given, and cannot be altered. This influence becomes most serious in overland lines during the period of low insulation. It will be clear that when measuring the capacity by charge test, the leakage current will add itself to the transient current, even if the time of making contact is reduced to a minimum. Hence in such a case the measured capacity of the line must be larger than the real capacity. But when measuring the capacity by discharge, a part of the total charge must leak out without being shown by the galvanometer. Hence the measured capacity in this case must be smaller than the real capacity.

Say that ρ' is the measured capacity by charge test, and ρ'' by discharge test, and that the real capacity is ρ, then we have

$$\rho' = \rho + \delta' \quad \text{charge test.}$$
$$\rho'' = \rho - \delta'' \quad \text{discharge test.}$$
$$\therefore \qquad \rho = \frac{\rho' + \rho''}{2} + \frac{\delta'' - \delta'}{2} = \frac{\rho' + \rho''}{2} \pm \delta$$

Now the two errors, although opposite in sign, cannot be equal. Supposing that the key contacts for charge and discharge tests last equally long, and that the line has not changed in insulation during the two experiments, it will be clear that $\delta' > \delta''$. Hence by taking the mean of the charge and discharge tests δ will be negative, or the result obtained will be larger than the real capacity of the line. But on account of not being able to fulfil the second condition perfectly, we know that the result by taking the mean is too small—*i.e.*, Δ is positive. Thus by taking the mean of the charge and discharge tests, we really bring the result as near to the truth as can be done without elaborate and intricate calculations.

VI. *Damping Force.*—If we could suspend a magnetic needle within a coil of wire, and exclude all foreign resistance against the motion of the needle, then clearly such a needle, when once deflected from its position of rest by a single impulse, would swing for *ever* with a *constant* amplitude of vibration, and the strength of the impulse (as for instance the strength of a transient current passed through the coil) would be accurately measured by the sine of half that amplitude. In practice, however, we *cannot* construct instruments of this kind—*i.e.*, the needle, when once deflected by a single impulse, will always swing to and fro with constantly decreasing amplitudes, until after a certain time it will come to rest. Hence, when measuring a transient current by the throw of a needle, the very force which ultimately arrests the motion of the needle must also act in diminishing the magnitude of the first throw, and therefore that throw will not measure accurately the strength of the transient current. In fact, without taking into account the external forces which act against the motion of the needle, the *measured* transient current must always be smaller than the *real* transient current.

The external forces which arrest the motion of the needle are: the friction on the pivot, or the torsion in the suspending fibre; the resistance of the air against the motion of the magnet and its accessories; and the reaction of the currents induced by the swinging magnet in all conductors in its neighbourhood. These induced currents are proportional to the velocity of the needle's motion, and act invariably, as Arago first proved, in a direction to bring the needle to rest. Induction currents of this nature are produced in the convolutions of wire, which in sensitive galvanometers must surround the needle as closely as practicable. Further, as galvanometers are usually more employed for measuring steady currents, in which case it is obviously convenient that the needle should come quickly to rest, special means are frequently adopted to increase the damping force of the instrument, either by attaching to the needle a vane swinging in air or any other resisting fluid, or better by closely surrounding the needle with a copper case. The aggregate of the forces mentioned above, which tend to arrest the motion of the needle, is called the "Damping Force."

It consists of two parts—namely, the one due to mechanical causes, and the other due to induction currents produced in the surrounding convolutions by the moving magnet. In galvanometers suitably constructed for the measurement of transient currents, the former may generally be neglected. The principle that a magnetic needle surrounded closely by a copper case comes quickly to rest has been applied in Dr. Wr. Siemens's "*Aperiodic Galvanometer*,"[1] in which the *damping force* is so great that the needle comes to rest after *one* swing, no matter of what amplitude. This instrument will therefore be eminently useful for executing a large number of consecutive tests of permanent currents, as for instance in insulator testing. When measuring transient currents, however, by the throw of the needle, the less damping force the galvanometer has the more exact the results will be without corrections; and instruments that have been specially constructed with great damping power, electrically or mechanically, are most unsuitable for the measurement of transient currents. Siemens's Aperiodic Galvanometer should not be employed for this purpose, nor should a Reflecting Galvanometer, the needle of which carries a vane (in air or other fluid). But even with ordinary test galvanoscopes, which are not specially constructed for large damping power, it will be always well to ascertain the amount of this damping force, in order to be able when desired to introduce the correction for the first throw.

VII. *Damping Correction.*—The quantity of electricity transmitted by a transient current of short duration is

$$q = k \sin\frac{a}{2}$$

where

$$k = \frac{2\,HT}{G\,\pi}$$

and T, it must be perfectly understood, is the time of a single vibration of the needle for *an infinitesimal ampli-*

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[1] Exhibited at the Vienna Exposition of 1873.

tude, and under the condition that the galvanometer in use exerts *no damping force* soever. But a galvanometer without damping force cannot be constructed, although special care may be taken not to increase it unnecessarily. Hence T cannot be found by direct measurement. Further, as the time of a single vibration of the needle increases with its amplitude, and as we can only observe the time of vibration for *finite* amplitudes, this constitutes a second reason why T cannot be directly observed. If we call T' the observed time of a single vibration for an average amplitude β, then the time T_0 to which T' approaches as the amplitude β becomes smaller and smaller is expressed as follows :—

$$T_0 = \frac{T'}{1 + \frac{1}{4}\sin^2\frac{\beta}{4} + \frac{9}{64}\sin^4\frac{\beta}{4} + \cdots}$$

Further, Gauss has shown that for small amplitudes the observed time of a single vibration of the needle, under the influence of the damping force, holds the following relation to the time which would be observed if the damping force were zero :

$$T'' = \frac{T_0\,\pi^2}{\pi^2 + \lambda^2} = \frac{T'}{(1 + \frac{1}{4}\sin^2\frac{\beta}{4} + \frac{9}{4}\sin^4\frac{\beta}{4} + \dots)} \cdot \frac{\pi^2}{\pi^2 + \lambda^2}$$

where λ is the logarithmic decrement of the vibration of the needle, to be explained further on.

Hence the final expression for q becomes

$$q = 2\,\frac{H}{G} \cdot \frac{\pi^2}{\pi^2 + \lambda^2} \cdot \frac{T'}{(1 + \frac{1}{4}\sin^2\frac{\beta}{4} + \frac{9}{64}\sin^4\frac{\beta}{4} + \cdots)}\sin\left(\frac{a}{2}\right) \cdots (32)$$

T' λ a and β are all four susceptible of direct measurement. Namely, T' is the observed time of a single vibration of the needle when swinging to and fro with the average amplitude β; λ is the logarithmic decrement of the vibration of the needle, *i.e.*, the logarithm of the ratio of two successive amplitudes; and a is the throw of the needle when the transient current passes.

It only remains, therefore, to describe how T', λ, a, and β may be found most correctly.

VIII. *Determination of* a, T', β, *and* λ.

§ 1. Determination of a.—Institute first a preliminary experiment, in order to know about the place on the scale to which the spot of light (using a reflecting galvanometer), or the index needle (using an ordinary galvanometer), is deflected by the passage of the transient current through the convolutions of the galvanometer. Then, fixing the eye on that place, repeat the observation, and read the throw of the needle with care. There will be no difficulty in doing this, even if a comparatively quick swinging magnet is employed, for at the point of maximum deflection, the index needle, or spot of light, changes the direction of its motion, necessitating a momentary rest at the time of reading. Several successive readings are, of course, always requisite in order to eliminate accidental errors, and also to get an idea of the correctness of the readings themselves. If a is taken by the charge test, it is necessary to put the line after each such reading directly to earth for a short interval of time, that the line may be sufficiently empty before the next following charge test. If a is measured by the discharge test, this precaution is not requisite.

As stated before, it is, however, best, in order to partly eliminate the influence of any existing leakage, to take successive readings of a by charge and discharge tests. If these two successive readings are sufficiently close to each other, the mean of the two readings will give the true deflection. If these two readings are not sufficiently equal, then it is always more correct to take the mean of the sines of the two readings as the sine of the true angle. Execute a sufficient number of these successive readings by charge and discharge test, and take either the mean of all as the correct deflection, or more accurately the mean of the sines of all the readings as the sine of the true angle. If amongst the many readings some are exceedingly large, while others are very low, and if the observer is further justified in taking them as possible observation errors, *i.e.*, not due to an actual change in the strength of the transient current to be measured, then such readings should be rejected. If the readings of a for successive charge and discharge tests are the same, or do not differ more from each other than is probably due to the reading error of the method employed, it follows that there is not sufficient leakage of the line to influence the throw of the needle. Further, if the different means of charge and discharge readings also correspond closely to each other, it follows that the line in question has not altered its electrical condition during the time of testing. The observations may then be trusted. Lines of low insulation, and especially when long, will not give such closely corresponding results, and the percentage of the mean of all the readings to the highest and lowest will give the error inherent in the observed result.

§ 2. Determination of T'.—By a single vibration is to be understood the motion of the needle from its maximum deflection on the one side of the point which represents its positions of equilibrium to its maximum deflection on the other side of that point, or *vice versâ;* the time occupied for the execution of this motion is called the *time of a single vibration of the needle,* and has been designated T'. To get T', therefore, it would appear only necessary to note the clock time at which two successive maxima deflections occur, their difference being equal to T'.

This, however, would be an inaccurate method, for, as stated before, the needle at each maximum remains momentarily at rest. Hence it is better to take the clock time at which the needle passes successively a place on the scale situated at or near the point of equilibrium. At this point the speed of the needle is greatest, and consequently time readings can be taken very exactly. Say that the clock time at which the needle passes through zero in the one direction is noted at t, the clock time at which the needle passes through zero when returning in the other direction is noted at t', and also again passing zero in the first direction at t'', then obviously $\frac{t + t'}{2} = T^{\text{I}}$ is the clock time at which the needle changed the direction of its motion on the one side of the scale, and $\frac{t' + t''}{2} = T^{\text{II}}$ is the clock time at which the needle changed the direction of its motion on the other side of the scale; hence $T^{\text{II}} - T^{\text{I}} = T'$ is the time of a single vibration of the needle. When ascertaining T' the following procedure should be adopted :—

In the first place have the instrument and scale in exactly the same position as when the reading of a was taken. Then set the needle swinging by means of a magnet, and as soon as the amplitude β becomes reduced to about a note the clock time at which the needle passes the zero of the scale, and simultaneously count zero; next note the clock time at which the needle again passes through zero on its return, and count 1; and so on to the nth passage of the needle through zero.

See the following table:—

No. of observation.	Clock time observed at which the needle is at or near its position of equilibrium.	Mean of two successive observed clock times.	T' evaluated from three vibrations.[1]
0	t		
		T	
1	t^{I}		
		T^{I}	$\frac{T^{III} - T}{3} = T_1$
2	t^{II}		
		T^{II}	
3	t^{III}		
		T^{III}	$\frac{T^{IV} - T^{I}}{3} = T_2$
4	t^{IV}		
		T^{IV}	
5	t^{V}		
		T^{V}	$\frac{T^{V} - T^{II}}{3} = T_3$
6	t^{VI}		

True time $$T' = \frac{T_1 + T_2 + T_3}{3}$$

It is clear that we should also have got a value of T' by simply taking the difference between the noted time t^{VI} and the beginning time t, and dividing it by the number of observations, *i.e.*,

$$T' = \frac{t^{VI} - t}{6}$$

but clearly this result, which does not take account of the intermediate readings t^{I} to t^{V}, cannot give such accurate results.

§ 3. Correction of T' with respect to amplitude.—Say that the amplitude at which the first time reading was taken was β', and at which the last time reading was taken was β'', then, strictly speaking, T' has been ascertained only for the average amplitude

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[1] The reason for calculating T' from the time three single vibrations take is simply that this method is the only one by which all the six observations have an influence on the mean, as a single substitution will show. Hence all observations have an influence on the final result. This is in fact the principle of using observations. It is obviously of no use to make a series of observations if the method of calculating the final result is of such a nature as to exclude some of the observations.

$$\beta = \frac{\beta' + \beta''}{2}$$

But, as stated before, we must know the time of a single vibration of the needle for an infinitesimal amplitude, which will be somewhat smaller than the observed time T'.

The correction given was

$$T_0 = \frac{T'}{1 + \frac{1}{4}\sin^2\frac{\beta}{4} + \frac{9}{64}\sin^4\frac{\beta}{4} + \cdots}$$

$$= T'\,(1 - \mu) \text{ approximately}$$

where $$\mu = \frac{1}{4}\sin^2\frac{\beta}{4} + \frac{9}{64}\sin^4\frac{\beta}{4} + \cdots$$

β	μ		β	μ		β	μ		β	μ	
0°	0·00000	...	11°	0·00058	10	21°	0·00210	20	31°	0·00457	29
1°	000	0	12°	069	11	22°	230	20	32°	487	30
2°	002	2	13°	080	11	23°	251	21	33°	518	31
3°	004	2	14°	093	13	24°	274	23	34°	550	32
4°	008	4	15°	107	14	25°	297	23	35°	583	33
5°	012	4	16°	122	15	26°	322	25	36°	616	33
6°	017	5	17°	138	16	27°	347	25	37°	651	35
7°	023	6	18°	154	16	28°	373	26	38°	686	35
8°	030	7	19°	172	18	29°	400	27	39°	723	37
9°	039	9	20°	0·00190	18	30°	0·00428	28	40°	0·00761	38
10°	0·00048	9	...	...	...	...	...	...	...	...	...

As $\beta = \frac{\beta' + \beta''}{2}$ is known, and T' has been determined, T_0 can be calculated.

When a reflecting galvanometer is used for taking the readings, then β is generally so small that (as the above formula shows) $T_0 = T'$ practically. But when, as often happens, an ordinary sensitive galvanoscope is employed, then the above correction may become necessary.

EXAMPLE.

The following experiments were made to determine T_0 *for a delicate testing galvanoscope.*

No. of observation.	Clock time observed at which needle is at or near its position of equilibrium.	Mean of two successive observed clock times.	Period evaluated from three vibrations.	
1 2 3 4 5 6 7	33" 41" 49" 56" 4" 10" 18"	37" 45" 52"·5 60" 7" 14"	$\frac{60 - 37}{3} = 7{\cdot}667''$ $\frac{7 - 45}{3} = 7{\cdot}333''$ $\frac{14 - 52{\cdot}5}{3} = 7{\cdot}167''$	Mean time $= \frac{7{\cdot}667 + 7{\cdot}333 + 7{\cdot}167}{3}$ $= \frac{22{\cdot}167}{3} = 7{\cdot}389''$ $\beta = \frac{55^\circ + 4^\circ}{2}$ $= 29{\cdot}5^\circ$
1 2 3 4 5 6 7	60" 8" 16" 23" 30" 37" 45"	4" 12" 19·5" 26·5" 33·5" 41"	$\frac{26{\cdot}5 - 4}{3} = 7{\cdot}500''$ $\frac{33{\cdot}5 - 12}{3} = 7{\cdot}167''$ $\frac{41 - 19{\cdot}5}{3} = 7{\cdot}167''$	Mean time $= \frac{7{\cdot}500 + 7{\cdot}167 + 7{\cdot}167}{3}$ $= \frac{21{\cdot}834}{3} = 7{\cdot}278''$ $\beta = \frac{61^\circ + 4^\circ}{2}$ $= 32{\cdot}5^\circ$
1 2 3 4 5 6 7	20" 28" 36" 43" 50" 57" 5"	24" 32" 39·5" 46·5" 53·5" 1"	$\frac{46{\cdot}5 - 24}{3} = 7{\cdot}500''$ $\frac{53{\cdot}5 - 32}{3} = 7{\cdot}167''$ $\frac{1 - 39{\cdot}5}{3} = 7{\cdot}500''$	Mean time $= \frac{7{\cdot}500 + 7{\cdot}167 + 7{\cdot}500}{3}$ $= \frac{22{\cdot}167}{3} = 7{\cdot}389''$ $\beta = \frac{50^\circ + 4^\circ}{2}$ $= 31^\circ$
1 2 3 4 5 6 7	38" 46" 54" 1" 8" 15" 23"	42" 50" 57·5" 4·5" 11·5" 19"	$\frac{4{\cdot}5 - 42}{3} = 7{\cdot}500''$ $\frac{11{\cdot}5 - 50}{3} = 7{\cdot}167''$ $\frac{19 - 57{\cdot}5}{3} = 7{\cdot}500''$	Mean time $= \frac{7{\cdot}500 + 7{\cdot}167 + 7{\cdot}500}{3}$ $= \frac{22{\cdot}167}{3} = 7{\cdot}389''$ $\beta = \frac{63^\circ + 4^\circ}{2}$ $= 33{\cdot}5^\circ$

$$\therefore\ T' = \frac{7{\cdot}389 + 7{\cdot}278 + 7{\cdot}389 + 7{\cdot}389}{4} = 7{\cdot}361''$$

$$\beta = \frac{29{\cdot}5 + 32{\cdot}5 + 31{\cdot}0 + 33{\cdot}5}{4} = 31{\cdot}5^\circ \text{ nearly.}$$

$$\therefore\ T_0 = 7{\cdot}361\,(1 - 0{\cdot}00534) = 7{\cdot}32''$$

§ 4. Determination of λ.—If we may consider the damping force as due only to induced currents produced in the conductors which surround a swinging magnet, then the decrease of arcs goes on in geometrical progression.

Let c be the constant ratio, then the logarithmic decrement is

$$\lambda = \log c$$

But if β_m denote the amplitude of the m^{th} vibration, and β_n denote the amplitude of the n^{th} vibration, then

$$c = \left(\frac{\beta_m}{\beta_n}\right)^{\frac{1}{n-m}}$$

Hence $$\lambda = \frac{\log \beta_m - \log \beta_n}{n - m} \quad \ldots \quad \ldots \quad (33)$$

where β_m and β_n are susceptible of observation, as well as m and n, and hence λ can be calculated. In order to obtain a correct value of λ, it is of course requisite to read a series of arcs, *i.e.*, a series of turning points of the needle. Further, the unavoidable observation errors in the readings of the arcs have the least possible effect on λ when $\frac{\beta_m}{\beta_n} = 3$ about. It must not be forgotten that the absolute magnitude of c depends for the same instrument also on the total resistance in circuit with the instrument. If the convolutions of the instrument are short-circuited, or the external resistance is zero, then obviously the induction currents produced in the coil must be strongest, or λ greatest. If the convolutions are left open, *i.e.*, the external resistance is infinite, then the induction currents produced are weakest, or λ is smallest.[1] Now, when measuring the capacity of a well insulated line, it would appear that the external resistance to the convolutions is almost always infinite. In reality, however, with respect to transient currents, this is not the case. For although a permanent current may find a resistance almost infinite, the transient current at the moment of charge, when the line is completely empty, finds a resistance $= 0$ (for a very short time only, it is true), and this resistance increases towards ∞ with the time, but for different lengths of line at different rates. It is requisite, therefore, to measure λ in each particular case, in order to get comparable results. In other words, when measuring the capacity of a line or a condenser by the throw of the needle, it is requisite to find λ for each such experiment when the line or the condenser actually is in connection with the instrument. This precaution becomes the more necessary the larger on the one hand the rate of damping is, and the more different in magnitude on the other hand the two capacities are which have to be compared together. In the following an example is given how λ can be best obtained from a series of observations.

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[1] Instruments which have been specially constructed with a damping arrangement (the magnet swinging in a copper case) will generally

Example.—λ is to be calculated from the following observations, taken with a sensitive test galvanoscope.

The needle when at rest points to zero, and the successive turning points on both sides of the zero have been noted.

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give a λ independent of the resistance of the circuit, *i.e.*, λ is the same when the convolutions are short-circuited or open, because in this case the whole damping force is due to the copper case. Such instruments where λ is large as stated before are, however, unsuited for measuring capacity by the throw of the needle. Sensitive galvanometers, in which the needle is surrounded as closely as possible by the convolutions, and which are not provided with special damping arrangements, have of course a small λ, which is, however, entirely dependent on the resistance external to the instrument. These are the instruments we use for measuring the capacity by the throw of the needle.

No. of Observation.	Observed Turning Points.	Arcs.
1	38°	64
2	26°	43
3	17°	30
4	13°	21
5	8°	14
6	6°	10
7	4°	

Hence λ is:

$$\text{for 1st and 4th arcs } \lambda = \frac{1}{3}(\log 64 - \log 21) = 0{\cdot}1613202$$

$$\text{for 2d and 5th arcs } \lambda = \frac{1}{3}(\log 43 - \log 14) = 0{\cdot}1624468$$

$$\text{for 3d and 6th arcs } \lambda = \frac{1}{3}(\log 30 - \log 10) = 0{\cdot}1590404$$

$$\text{or mean } \lambda = 0{\cdot}1609358$$

which is the value to be used in the formula.

It must not be forgotten that the correction for damping as introduced in the formula is correct only when the arcs through which the needle swings are very small; but the correction, although not quite exact, is nevertheless better than none at all.

IX. *Method of Comparing Capacities by the Balancing of Charges.* — Let the capacities of the two condensers (cables, artificial cables, overland lines, or accumulators) to be compared be denoted by S and S'. We shall assume at first that the insulation of the condensers is perfect, and that they do not in themselves contain any electromotive force.

Connect the *outer* coatings of both condensers permanently to earth.

Put the *inner* coating of the condenser S in communication with an electric source of constant potential V, and maintain the connection for sufficient time to charge the condenser fully. Let Q be the quantity of the charge received by S. Similarly charge the *inner* coating of the condenser S' to its full from a source of constant potential V'. Let Q' be the quantity of the charge received by S'. Next connect the *inner* coatings of the two condensers together; allow sufficient time to elapse for electrical equilibrium to supervene; and by means of an *electrometer* observe the potential U of the system formed by the two *inner* coatings that have been connected together. Then[1]

$$\frac{S'}{S}=\frac{\frac{V}{U}-1}{1-\frac{V'}{U}}$$

If we adjust the potentials V and V' so that Q' shall be equal, but of opposite sign, to Q, then obviously the two charges will exactly neutralise one another, and U will be zero. When[2]

$$\frac{S'}{S}=\frac{V}{V'}$$

---

[1] $$U=\frac{Q+Q'}{S+S'}$$

But $$Q=S\ V$$

and $$Q'=S'\ V'$$

$\therefore$ $$U=\frac{S\ V+S'\ V'}{S=S'}$$

Whence $$\frac{S'}{S}=\frac{\frac{V}{U}-1}{1-\frac{V'}{U}}$$

where the potentials V and U, and V' and U, can be directly compared by the electrometer.

[2] We had $$U=\frac{S\ V+S'\ V'}{S+S'}$$

Putting now $U=0$, and taking V and V' of opposite signs, we have

$$\frac{S'}{S}=\frac{V}{V'}$$

Under these circumstances the *electrometer* may be replaced by a *galvanometer*, the one pole of which is put to earth, to observe potential of the system.

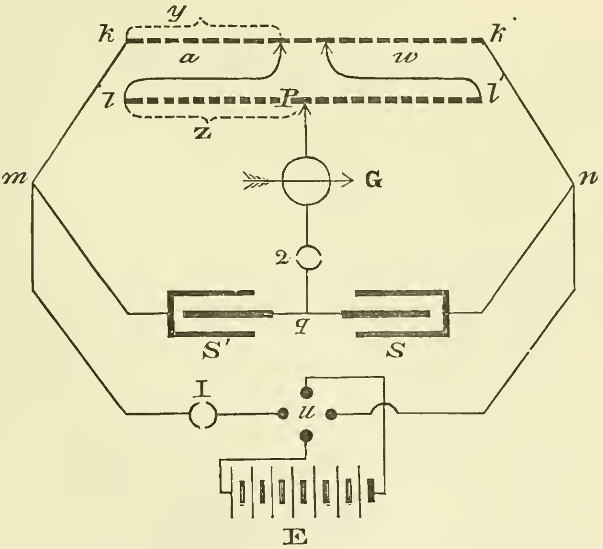
The following form is the most convenient to give this method in practice, and it admits of either an electrometer or a galvanometer being employed.

Thomson's method of comparing capacities.[1] This method of comparing capacities is analogous to Wheatstone's method of comparing resistances by means of the Bridge. (See Fig. 10 and compare it with Fig. 1.)

S and *S′* are the two capacities which are to be compared. All the other letters have the same meaning as in Fig. 1, and those not mentioned will be explained further on.

First thoroughly discharge the condensers, and then make contact at (1) permanently, and adjust *w* until

Fig. 10.



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[1] Sir William Thomson, Journal of the Society of Telegraph Engineers, vol. i. p. 397.

there is balance in G when contact is made at (2). Then, as before,[1]

$$\frac{S'}{S}=\frac{\frac{V}{U}-1}{1-\frac{V'}{U}}$$

$$\therefore\quad \frac{S'}{S}=\frac{a}{w} \qquad \ldots \qquad \ldots \qquad \ldots \qquad (34)$$

It must be understood that each time after contact (2) is closed, the condensers must be discharged before recommencing operations.

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[1] Let V be the potential at m, V' the potential at n, U at p, and U' at q.

Then, when balance is established, U' must be equal to U, and therefore the current from m to n through a and w must be uniform, that is

$$\frac{V-U}{a}=\frac{U-V'}{w}$$

$$\therefore \qquad \frac{V-U}{U-V'}=\frac{a}{w}$$

or

$$\frac{\frac{V}{U}-1}{1-\frac{V'}{U}}=\frac{a}{w} \qquad \ldots \qquad \ldots \qquad \ldots \qquad (a)$$

Further, when electrical equilibrium is established in the branch containing S and S', *i.e.*, when the condensers are fully charged, the quantities of the inducing and induced electricities must be equal. that is

$$S\,V+S'\,V'=U\,(S+S')$$
$$S\,(V-U)=S'\,(U-V')$$

or

$$\frac{\frac{V}{U}-1}{1-\frac{V'}{U}}=\frac{S'}{S} \qquad \ldots \qquad \ldots \qquad \ldots \qquad (b)$$

Combining (a) and (b)

$$\frac{S'}{S}=\frac{a}{w}$$

Whenever we unplug or plug up resistance in w, the total resistance $a+w$ between m and n will be altered, and therefore the current through $a+w$ must change, and consequently the charges of the condensers S and S' will be temporarily disturbed. Hence it is preferable that p should be made a sliding contact, and that $a+w$ should be kept constant, and consist of a series of coils of equal resistance (the magnitude of which should depend on the sensibility of the testing instrument). To obtain, however, the requisite range and sensibility with such an arrangement, an enormous number of coils, each of small resistance, would be necessary. Varley's ingenious slide resistance, a description of which follows, obviates the necessity of such a costly and bulky apparatus.

NOTE.—*Varley's Slide Resistance.*

This consists of two series of coils of equal resistances—a primary series $k\ k'$ and a secondary series $l\ l'$ (see Fig. 8). The primary series consists of $n+1$ coils, each with a resistance R, and has a total resistance of $(n+1)\ R$. The secondary series consists of n coils, each with a resistance $r = \frac{2\ R}{n}$, and has a total resistance $n\ r = 2\ R$. One end of the primary series of coils is connected to m, and the other end of the same series is connected to n (see Fig. 8). Along the primary series of coils move two sliding contact pieces, insulated from one another, but rigidly fixed together at such a distance apart that when the one contact piece is touching one stud the other contact piece is touching the *next stud but one.* Hence the primitive resistance between the two contact pieces always is that of two of the primary coils $= 2\ R =$ total resistance of secondary series of coils. One end of the secondary series of coils is connected to the one sliding contact of the primary series, and the other end of the secondary series of coils is connected to the other sliding contact of the primary series. Thus the resistance between the two sliding contacts of the primary series becomes $\frac{2\ R \times 2\ R}{2\ R + 2\ R} = R =$ resistance of a single coil of the primary series. Hence the resistance between m and n is $= n\ R$. Along the secondary series of coils moves a sliding contact piece representing the point p of the Bridge. The potential between k and k' falls regularly along the primary series of coils, the decrement from coil to coil being $\frac{V-V'}{n}$. The two coils included between the sliders act as a single coil, on account of being shunted by a resistance (that of the secondary series of coils) equal to their own. Hence the potential falls $\frac{V-V'}{n}$ between the two ends of the secondary series of coils. Again the potential along the secondary series of coils $l\ l'$ falls regularly, the decrement from coil to coil being clearly $= \frac{1}{n} \frac{V-V'}{n} = \frac{V-V'}{n^2}$. Hence by moving the sliding contact p from one coil of the secondary series to the next, we vary the potential by $\frac{V-V'}{n^2}$, or by the same amount as if p travelled along a single series of coils between m and n consisting of n^2 coils each with a resistance of $\frac{R}{n}$. For instance, say $R = 1000$ ohms, $n = 100$, and $r = \frac{2\ R}{n} = \frac{2000}{100} = 20$ ohms, as is the case in the slide resistance boxes in use in the Testing Room at Alipore, then the variation of potential along the secondary coil is the same as if there were a single series of 10000 coils having 10 ohms resistance each. Let $y =$ the number we read on the primary scale (*i.e.*, the number of coils intervening between k and the first sliding contact), and $z =$ the number we read on the secondary scale; then[1] (see Fig. 8)

$$\frac{w}{a} = \frac{n^2}{n\,y + z} - 1 = \frac{1}{\frac{y}{n} + \frac{z}{n^2}} - 1$$

When

$$n = 100$$

$$\frac{w}{a} = \frac{1}{x} - 1$$

where $x = \frac{y}{10^2} + \frac{z}{10^4}$, *i.e.*, y represents hundredths, and z represents ten thousandths, the total resistance between m and n being taken as unity.

---

[1]
$$\frac{a}{w} = \frac{y\,R + z\,\frac{R}{n}}{\{n - (y+1)\}R + (n-z)\,\frac{R}{n}}$$

§ 1. Influence of Leakage.—It is clear that so long as the capacities to be compared are those of ordinary condensers, *i.e.*, with only capacity, and no sensible conduction resistance in the plates, the leakage can have no influence soever on the final result. But when we have to compare the capacity of a telegraph line with the capacity of an ordinary condenser, then, although the leakage in itself may be perfectly insensible, the measured potential V' at the home end does not represent the potential at all the points of the line in question, since the potential of a Telegraph line along the wire, when not perfectly insulated, must decrease with the distance from the battery. The *average* potential of a line not perfectly insulated we will call v', then the quantity of electricity with which the line is charged is $v'\ S'$, and at balance we have

$$\frac{S'}{S} = \frac{V}{v'}$$

V we measure directly, but v' is unknown; and we are given only one value of the decreasing series of that potential, namely, V'.

If we take S' to be the capacity of a Telegraph line whose insulation and conduction are uniform, then[1]

$$= \frac{(n\,y + z)\,R}{(n^2 - n\,y - n + n - z)\,R}$$

$$= \frac{n\,y + z}{n^2 - (n\,y + z)}$$

$$= \frac{1}{\dfrac{n^2}{n\,y + z} - 1}$$

$$\therefore \quad \frac{w}{a} = \frac{n^2}{n\,y + z} - 1$$

[1] Ohm has shown that the potential v at any point of a prismatic conductor, uniform in conduction, insulation, and capacity, is expressed

$$v' = \frac{V'}{N\sqrt{\frac{r}{i}}} \cdot \frac{\epsilon^{N\sqrt{\frac{r}{i}}} - 1}{\epsilon^{N\sqrt{\frac{r}{i}}}}$$

$$= V'\frac{M}{N}\text{ say,} \qquad \ldots \qquad \ldots \qquad (35)$$

where N is the length of the line, i is the insulation per

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as follows when the line is fully charged, so that the potential at every point remains constant with respect to time:

$$= \epsilon^{-mx}V'$$

where x is the distance of the point in question from the battery, V' is the potential at the home end of the line, ϵ is the base of the Napierian system of logarithms, and $m = \sqrt{\frac{r}{j}}$, r being the conduction resistance, and j the insulation resistance per mile. The line is supposed to be insulated at the distant end.

The charge δQ on the length δx is

$$\delta Q = \frac{S'}{N} v\,\delta x$$

$$= \frac{S'}{N}\epsilon^{-mx}V'\,\delta x$$

where N is the length of the line, and S' is its absolute capacity.

Hence the total charge of the line is

$$Q = \frac{S'}{N}V'\int_0^N \epsilon^{-mx}\,dx$$

$$= S' \cdot \frac{V'}{N} \cdot \frac{1 - \epsilon^{-mN}}{m}$$

But if v' = the *average* potential of the line, then

$$Q = S'\,v'$$

whence

$$v' = \frac{V'}{N} \cdot \frac{1 - \epsilon^{-mN}}{m}$$

$$= \frac{M}{N}V'$$

where $M = N$ when $i = \infty$.

unit of length, r is the conduction resistance of the wire per unit of length, and V' is the potential actually measured.

Hence the corrected formula is

$$\frac{S'}{S} = \frac{NV}{MV'}$$

or substituting for $\frac{V}{V'}$ the readings $\frac{a}{w}$, we have

$$S' = \frac{a}{w} \cdot \frac{N}{M} \cdot S \quad \ldots \quad \ldots \qquad (36)$$

where

$$M = \frac{\epsilon^{N\sqrt{\frac{r}{i}}} - 1}{\sqrt{\frac{r}{i}} \; \epsilon^{N\sqrt{\frac{r}{i}}}}$$

For $i = \infty$, M becomes $\frac{0}{0}$, which, as can be proved, has the value N. That is to say, when the leakage of the line in question is imperceptible, we have the original formula

$$\frac{S'}{S} = \frac{a}{w}$$

But when the leakage is not imperceptible, then M is invariably smaller than N, and hence, by neglecting the correction, we get S' too small. M becomes smaller for a constant $\frac{r}{i}$ the larger N is, and for a constant N the larger $\frac{r}{i}$ is.

EXAMPLE.—A telegraph line 500 miles (of 1760 yards) in length is to be tested for capacity by comparing it with the capacity of an ordinary condenser of 1 M. F. capacity.

Further, the line has 10 megohms insulation per mile, and its conduction resistance is 10 ohms per mile. Thus

$$N=500 \text{ miles}$$
$$i=10\ \Omega$$
$$r=10\ \omega$$

$$\therefore \qquad M=\frac{\epsilon^{500\sqrt{\frac{10\omega}{10\,\Omega}}}-1}{\sqrt{\frac{10\,\omega}{10\,\Omega}}\;\epsilon^{500\sqrt{\frac{10\,\omega}{10\,\Omega}}}}$$

$$=\frac{\epsilon^{\frac{1}{2}}-1}{0{\cdot}001\epsilon^{\frac{1}{2}}}$$

$$=\frac{\sqrt{2.718}-1}{0{\cdot}001\ \sqrt{2{\cdot}718}}=394 \text{ miles about.}$$

Hence, in this case,

$$S'=\frac{a}{w}\cdot\frac{500}{394}\cdot S$$

$$=1{\cdot}27\frac{a}{w}\cdot S$$

or by omitting the correction we should get S' 27% too small.

§ 2. Approximate value of $\frac{M}{N}$. Formula (35) gave the exact correction required to determine accurately the capacity of a Telegraph line, when its insulation is not so great that the leakage can be neglected. A very good approximate value for $\frac{M}{N}$, and one not requiring reference to a table of logarithms, is[1]

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[1] The exact value of M is:

$$M=\frac{1-\epsilon^{-mN}}{m}$$

Expanding ϵ^{-mN} in series, we have :—

$$\frac{M}{N}=\frac{2-N\sqrt{\frac{r}{i}}}{2} \qquad \ldots \qquad (37)$$

Hence formula (36) becomes

$$S'=\frac{a}{w}\left(1-\frac{N}{2}\sqrt{\frac{r}{i}}\right)S \qquad \ldots \qquad (38)$$

§ 3. Influence of foreign E. M. F. When comparing the capacity of a Telegraph line with that of an ordinary condenser, it may not unfrequently happen that the line in itself contains an E. M. F. due to the combined influence of many causes. This E. M. F. gives rise to what has been termed a *natural current.* Such a current in the present case can be easily detected.

Close contact (2) but leave contact (1) open (see fig. 8), when, if a sensible natural current be present in the line, a permanent deflection will be observed on the galvanometer G. This current, although perhaps variable with respect to time, may remain sufficiently constant during two consecutive observations, in which case its effect may be eliminated as follows :—

$$1-\epsilon^{-mN}=mN-\frac{1}{1\cdot2}m^2N^2+\frac{1}{1\cdot2\cdot3}m^3N^3-\cdots$$

$$=mN\left(1-\frac{1}{1\cdot2}mN+\frac{1}{1\cdot2\cdot3}m^2N^2-\cdots\right)$$

$$\therefore\ \frac{M}{N}=1-\frac{1}{1\cdot2}mN+\frac{1}{1\cdot2\cdot3}m^2N^2-\ldots$$

Neglecting all terms after the second, as may be done without sensible error, provided $\frac{r}{i}$ is small, we have

$$\frac{M}{N}=\frac{2-N\sqrt{\frac{r}{i}}}{2}$$

Close contact (1), take successive readings with reversed testing battery (change the poles of E at u), and adjust the ratio $\frac{a}{w}$ by moving the sliding contacts until on making contact at (2) *the same deflection* is produced on the galvanometer G whether the positive or the negative pole of the testing battery be to earth. This deflection becomes zero when there is no natural current in the line. It must not be forgotten that it is essential to allow sufficient time after each reversal of the battery before closing contact (2), in order that the opposite charges of S and S' may arrive at the desired electrical equilibrium. Further, that contact (2) should be made sufficiently long to allow any disturbance of electrical equilibrium to take place, and show itself as a current in the galvanometer.

§ 4. Advantages of the method. Supposing that we introduce the correction for insulation, and that we eliminate the influence of the natural current in the line, it is clear that this method must give exceedingly accurate results. For, in the first place, it is a perfectly *null* method; that is to say, the two opposite charges of the two capacities are made to neutralise each other. Hence the final reading is independent of the nature and construction of the testing instrument: sensitiveness only is requisite. Further, retardation has no influence on the final reading of the zero, although it must have influence on the strength of the current which passes through the galvanometer before electrical equilibrium is arrived at. But this current serves only as an indicator to guide us to the zero point, and its magnitude is not made use of in taking the final reading. Hence the method is equally accurate for comparing the capacities of two ordinary condensers as for comparing the capacity of a long submarine cable with the capacity of an ordinary condenser. Only of course for the sake of sensibility near the zero point it is advisable to make the two capacities under comparison not too different from each other.

§ 5. Defects of the method.—It will be clear that unless the insulation of the two condensers to be compared be perfect, or, more generally, unless the insulation of the two condensers to be compared be in the inverse ratio of their electrostatic capacities, there will be a permanent difference of potentials between p and q due to leakage, and it will be impossible to obtain accurate balance.

X. *To localise an Earth.*

§ 1. Dead earth on a single line.—When a dead earth occurs on a single line, communication between the two terminal stations is necessarily stopped, and consequently the localisation of the fault must be undertaken by the testing station unassisted by the distant station, unless special arrangements to meet such a contingency have been come to beforehand between the two stations.

We shall first suppose that the line in question consists of a wire of uniform gauge, and that it is generally so highly insulated that the total conduction resistance may be neglected as compared with the absolute insulation of the line. Then, measuring the resistance w of the line from the testing station to the fault (by any of the available test methods), we have obviously

$$n\,k = w$$

Whence $$n = \frac{w}{k} \text{ miles} \quad \dots \quad \dots \quad (39)$$

where k is the conduction resistance of the line per mile corrected to the temperature[1] the line probably had when the localisation test was made. If the line contains different gauges of wire, the order of which, as well as their lengths and mileage resistances, are known, then the calculation of n is not so direct. In this case we must first ascertain the position of a certain point p in the line from which the gauge remains constant up to the fault. Say that η is the length of any gauge up to that point, and ρ its resistance per mile, then we have

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[1] Iron wire varies in resistance from 0·2 to 0·35 per cent. for each degree Fahrenheit. We use therefore the mean 0·275%. The average temperature in India is about 80° F., and, supposing that the resistance

$$n = \Sigma(\eta) + \frac{w - \Sigma(\eta\,\rho)}{k} \quad \ldots \quad \ldots \quad (40)$$

Example.—Between two stations, *A* and *B*, there is only a single wire on which interruption occurs due to a *dead earth*. The distance between *A* and *B* is 200 miles. The order of the gauges, their lengths and resistances, are :

Miles from A towards B.	I. W. G.	Resistance per mile at 80° Fahr. in ohms.
10	No. 16	15·75
50	No. 24	10·50
40	No. 50	5·04
20	No. 48	5·25
80	No. 24	10·50

By experiment it is ascertained that $w = 917$ ohms. The localisation test was made at about 8 hours during the month of January when the temperature (dry bulb)

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per mile of the different gauges in India is known for that temperature (see Table, Appendix I.), then we can always calculate the resistance of any gauge for any other temperature t larger or smaller than 80° by the following formula. (See Table, Appendix II.)

$$k_t = \frac{1 + (t \quad - 32)\,0{\cdot}00275}{1 + (80 - 32)\,0{\cdot}00275}\,k_{80}$$

$$= \{0{\cdot}883 + 0{\cdot}00243\,(t - 32)\}\,k_{80}$$

at the one station was 62°, and at the other station was 60°, or average = 61°. Further, it is known from the regular tests that the insulation of this wire at the hour of the day and season of the year is never less than 10 Ω per mile. Now we observe that the conduction resistance to the end of the first 100 miles is

$$\begin{aligned}\Sigma\,(\eta\,\rho) &= 884{\cdot}1 \text{ at } 80^\circ \text{ Fahr.}\\ &= 843{\cdot}8 \text{ at } 61^\circ \text{ Fahr.}\end{aligned}$$

The fault, therefore, is on the No. 48 wire, the resistance of which is 5·0 ω per mile at 61° Fahr. Hence we have

$$n = \Sigma\,(\eta) + \frac{w - \Sigma\,(\eta\,\rho)}{k}$$

$$= 100 + \frac{917 - 843{\cdot}8}{5} = 114{\cdot}6 \text{ miles from the testing station.}$$

§ 2. Errors of the method.—In the first place, the resistance of an "earth," although perhaps small enough to cause total interruption with the receiving instruments and signalling batteries employed, may still be quite large enough to introduce a sensible error in the result, if neglected. In other words, on account of the resistance of the earth not being necessarily zero, or even not approximately so, the distance n calculated by formulæ (39 and 40) from the measured value w must invariably be a *maximum.*

In the second place, the resistance of an "earth" is variable, not only in itself, but principally owing to the test currents which invariably polarise the fault. This fact introduces uncertainty in getting the right value for w, *i.e.*, different successive determinations of w will always give different values for w. In addition to this, there may exist, as in fact is generally the case, a natural current in the line between the earth of the testing station and that of the fault.

In the third place, the absolute conduction resistance of an overland Telegraph line cannot always be neglected against the absolute insulation of the line; and if this is true of the whole line, it will also be true of any section of that line, although to a lesser extent. In other words, we do not know by what value of k the resistance w is to be divided.

If we call the value of k by which w should be divided ξ, and we denote the resistance of the fault by z, the true value of n would be

$$n = \frac{w - z}{\xi}$$

As the distant station is supposed not to be able to assist, there are no means of getting the value of z, except by conducting the tests in such a manner as to probably make z as small as possible. This we do as follows:—

We measure w finely by a positive current from a strong battery, when it will be observed that w increases with the time this positive current is kept on.

As soon as w is observed to remain approximately constant, we reverse the battery, *i.e.*, measure w with a negative test current, when it will be observed that w decreases to a certain point, at which it will begin to steadily increase again: this is the time for reading w.[1]

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[1] A positive test current oxidises the fault, and covers it with salts, resulting finally in a high but constant z. When now a negative test current is sent, hydrogen is developed which reduces the salts, lowering steadily the resistance z, until the moment arrives when all the salt produced has been reduced, and the exposed surface of the wire becomes metallic, at which point hydrogen will adhere to the wire, again increasing the resistance z. Hence the moment when w reaches its minimum, indicated by its beginning to increase again, is the time w should be

After having ascertained in this manner the minimum w, *i.e.*, having reduced z as much as possible, we see whether the faulty line contains a *natural current*. If not, the w thus found may be used directly. If, however, a natural current is observed, then reduce the E. M. F. of the testing battery as much as the sensitiveness of the testing instrument will allow of, and take a set of readings with successive positive and negative test currents. These readings should be taken as quickly as possible, in order not to allow even the weak testing current any time to polarise the fault. From the two values w' and w'' obtained in this way, the right w can be calculated as usual.

Now if for ξ we use the value k, the true conduction resistance per mile of the line, we shall get

$$n' = \frac{w}{k} < x$$

and if for ξ we use the value k', the measured conduction resistance of the whole line, at a time of the day and season of the year the same as when the localisation test was made (this value is taken from the regular test records of the line), then we shall get

$$n'' = \frac{w}{k'} > x$$

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read. The phenomenon just described is seen very decidedly when the faulty place in the line is of small area, as for instance might be the case with a submarine cable, the dielectric of which had been perforated at a single point. In the case of overland lines where the area of the fault, *i.e.*, surface of wire in contact with the damp ground or water, may be considerable, putting on a positive test current may have only a very slight effect in raising w; *i.e.*, w will remain almost constant, while the subsequent negative current will also have little effect in decreasing w. Then of course we conclude that we cannot reduce z approximately to zero, although by this procedure we must obtain the smallest z.

Hence by taking the mean of these two results we shall obtain a value for n which will be nearer the truth than either of them.

Thus

$$n = \frac{w}{2}\left(\frac{1}{k} + \frac{1}{k'}\right) \quad \ldots \quad \ldots \quad (41)$$

Example.—On a single line 270 miles in length, consisting throughout of No. 24 wire, a "dead earth" occurs, and an attempt to measure w shows it to be very variable.

The following readings are then taken with a testing battery of 30 cells, copper to line:

Hour.	Observed resistance.
10-17	2449
10-19	2570
10-21	2598
10-23	2605
10-25	2607
10-27	2608
10-29	2623
10-31	2650
10-33	2697
10-35	2728
10-37	2739
10-39	2741
10-41	2741

Testing battery reversed, zinc to line:

10-43	2395
10-44	2325
10-45	2270
10-46	2140
10-47	2135

Testing battery reduced to 5 cells

	+	−	
		2250	47°*L*
	2503		
		2266	
	2474		
		2197	
	2480		
		2275	
	2475		
Means:	+2483	−2247	

$$\pm 2365$$

Dividing by 10·3, the resistance of No. 5 wire at 73° F.,

$$n' = \frac{2365}{10{\cdot}3}$$

$$= 230 \text{ miles about.}$$

The measured conduction resistance, however, of this line is only 9·8 ohms per mile, which would give

$$n'' = \frac{2365}{9{\cdot}8}$$

$$= 241 \text{ miles about.}$$

Taking the mean of these results as the most probable value, we have

$$n = \frac{n' + n''}{2}$$

$$= \frac{230 + 241}{2}$$

$$= \frac{471}{2}$$

$$= 235{\cdot}5 \text{ miles.}$$

On this occasion the wire was found off the insulators and resting in surface water on marshy ground at 235 miles from the Testing Station.

§ 3. Case of a line containing several gauges of wire.—When a line contains several different gauges of wire, the order and lengths of which are known, then, although the experimental determination of w is precisely the same as before, the formula by means of which n is to be calculated becomes somewhat different, namely :

$$n=\Sigma(\eta)+\frac{w'}{2}\left(\frac{1}{k}+\frac{1}{k'}\right) \quad \ldots \quad \ldots \quad (42)$$

where

$$w'=\frac{w-\lambda}{1-\frac{\Sigma(\eta)\,(w-\lambda)}{J}}-\lambda' \ldots \quad \ldots \quad (43)$$

w' is the resistance that would be observed if a measurement were made from a certain point p in the line to the fault ; and λ and λ' are known resistances which indicate the position of the resultant fault of the section between the testing station and the same point p of the line. This point p is nearer than the fault to the testing station, and is so situated that from p to the fault the gauge of the wire is constant. J is the corrected insulation of the line per mile, supposed to be uniform. The value of J may be either taken from the test records, or may better be calculated from the following formula :

$$J=\frac{N\,l'\,(N\rho'-l)}{l+l'-N\rho'} \quad \ldots \quad \ldots \quad (44)$$

where N is the known length of the line in miles ; ρ' is the average conduction resistance of the line per mile, taken from the test records—such tests being selected as were made at about the same season of the year and hour of the day as when the localisation test was made ; and l and l' are resistances indicating the position of the resultant fault in the line, the insulation being supposed to be uniform throughout.

l and l' can be calculated by means of formula (22), p. 81, and their relative values remain unchanged so long as the insulation keeps uniform and the gauges of the wire are not altered. λ and λ' can also be calculated by the same formula.

k is the real conduction resistance of the wire in which the fault exists. (This value is known from Appendix VII.)

k' is the measured conduction resistance of the section in which the fault exists, which would be found by actually measuring the resistance of that section and dividing the result by the number of miles it is in length. This we cannot do, but we can obtain an approximation towards the desired result in the following manner :

Calculate the value of n roughly by assuming $k'=k$. Call this approximate value of $n=n'$. Then

$$k' = \frac{k}{2} + \frac{k}{2 + \frac{k\,\{n' - \Sigma\,(\eta)\,\}^2}{J}} \quad \ldots \quad (45)$$

With this value of k' calculate the true n, using for J the value found from formula (44). An example will make the procedure clear.

Example.—In a single line, 390 miles in length, a "dead earth" occurs; and by experiment it is found that $w = 2711$ ohms. The order and length of the gauges of wire in the line are as follows, commencing from the testing station :—

WIRE.		LENGTH.		RESISTANCE.	
I. W. G. No.	Resistance per mile at 80° F. in ohms.	Of section only in miles.	Total to end of section in miles.	Of section only in ohms.	Total to end of section in ohms.
24	10·50	50	50	525	525
50	5·04	100	150	504	1029
16	15·75	50	200	787·5	1816·5
24	10·50	80	280	840	2656·5
48	5·25	20	300	105	2761·5
50	5·04	90	390	453·6	3215·1

The resistance w found by measurement is 2711 ohms; and, therefore, if the insulation of the line between the testing station and the fault were perfect, the fault would be in the No. 48 wire.

Assuming for the moment this to be the case, to give us a starting-point for our calculations, we have :—

$$\begin{aligned} \Sigma\,(\eta) &= 280 \text{ miles} \\ N &= 390 \quad ,, \\ \lambda &= 1217{\cdot}4 \text{ ohms} \\ \lambda' &= 1439{\cdot}1 \quad ,, \\ l &= 1702{\cdot}6 \quad ,, \\ l' &= 1512{\cdot}5 \quad ,, \end{aligned} \quad \left.\vphantom{\begin{matrix}a\\a\\a\\a\end{matrix}}\right\} \text{calculated by formula 22.}$$

The localisation test was made during fair weather in the month of January at 10 hours, and a number of tests made at corresponding periods give the average conduction resistance of the whole line to be $\rho' = 7{\cdot}3$ ohms.

$$\text{Thus } J = \frac{390 \times 1512{\cdot}5\,(390 \times 7{\cdot}3 - 1702{\cdot}6)}{3215{\cdot}1 - 390 \times 7{\cdot}3} \text{ by formula (44)}$$

$$= 1833884\ \omega$$

$$\text{and} \quad w' = \frac{2711 - 1217{\cdot}4}{1 - \dfrac{280\,(2711 - 1217{\cdot}4)}{1833884}} - 1439{\cdot}1 \text{ by formula (43).}$$

$$= 495{\cdot}7\ \omega$$

$$\therefore \quad n' = 280 + \frac{495{\cdot}7}{5{\cdot}25} = 374{\cdot}42 \text{ miles}$$

Further

$$k' = \frac{5{\cdot}25}{2} + \frac{5{\cdot}25}{2 + \dfrac{5{\cdot}25\,(94{\cdot}42)^2}{1833884}} = 5{\cdot}22\ \omega \text{ by formula (45)}$$

Thus $n'' = 280 + 95{\cdot}02 = 375{\cdot}02$ miles

Whence

$$n = \frac{n' + n''}{2} = 374{\cdot}72 \text{ miles from testing station.}$$

From this result we see that the fault cannot be in the No. 48 gauge, but must lie beyond it, since the distance to its end remote from the testing station is only 300 miles. The fault, therefore, must be in the No. 50 gauge.

Taking now

$\Sigma\ (\eta)=300$, we have
$N=390$ miles
$\lambda=1710{\cdot}6$ ohms
$\lambda'=1050{\cdot}9$ „
$l=1702{\cdot}5$ „
$l'=1512{\cdot}5$ „
$J=1833884$ „

$$\text{Thus } w'=\frac{2711-1710{\cdot}6}{1-\dfrac{300\ (2711-1710{\cdot}6)}{1833884}}-1050{\cdot}9=150{\cdot}4\ \omega$$

$$n'=300+\frac{150{\cdot}4}{5{\cdot}04}=329{\cdot}82 \text{ miles}$$

$$k'=\frac{5{\cdot}04}{2}+\frac{5{\cdot}04}{2+\dfrac{5{\cdot}04\ (29{\cdot}82)^2}{1833884}}=5{\cdot}04\ \omega \text{ nearly}$$

$$n''=300+\frac{150{\cdot}4}{5{\cdot}04}=329{\cdot}82 \text{ miles}$$

Whence $n = 329{\cdot}82$ miles from testing station. Had we not taken the leakage due to imperfect insulation of the wire into account, we should have found $n = 290{\cdot}40$ miles only, representing an error of no less than 39·42 miles, or 12°/ₒ in the result.

§ 4. Localisation of partial earth in a single wire.—In this case correspondence is only rendered imperfect. and therefore the testing station is able to communicate orders to the distant station. Three measurements, then, can clearly be made, viz., we can measure the resistance offered by the line when (1) the distant end is connected to earth through a known and constant resistance r, (2) the distant end is put directly to earth, and (3) the distant end is insulated.

Thus, making the above three measurements, and assuming the insulation of the line to be perfect everywhere except at the fault, we have

$$W = x + \frac{z\,(L - x + r)}{z + L - x + r} \quad \dots \qquad (a)$$

$$w = x + \frac{z\,(L - x)}{z + L - x} \quad \dots \quad \dots \qquad (b)$$

$$I = x + z \quad \dots \quad \dots \qquad (c)$$

where L is the true conduction resistance of the line at the time of making the observations, z is the resistance offered by the fault, and x is the resistance from the testing station to the fault.

From these three equations it follows that

$$\left.\begin{aligned} z &= \sqrt{\frac{(I - W)\,(I - w)\,r}{W - w}} \\ \text{and} \qquad x &= I - z \end{aligned}\right\} \quad \dots \qquad (46)$$

Should no known and constant resistance be available in the distant station, the first measurement (a) must be omitted ; and the value of x must be found from equations (b) and (c), thus

$$\left.\begin{aligned} x &= w - \sqrt{(L - w)\,(I - w)} \\ \text{and} \qquad z &= I - x \end{aligned}\right\} \quad \dots \qquad (47)$$

Formula (46) is preferable to formula (47), because r is more accurately known, and can be more accurately corrected for temperature, than L can possibly be.

Substituting the value of x for w in formulæ (39) and (40), we have

$$n = \frac{1}{k}\left\{I - \sqrt{\frac{(I - W)\,(I - w)\,r}{W - w}}\right\} \quad \dots \quad \dots \quad \dots \qquad (48)$$

when the wire is of uniform gauge throughout the line; and

$$n=\Sigma\,(\eta)+\frac{1}{k}\Big\{I-\sqrt{\frac{(I-W)\,(I-w)\,r}{W-w}}-\Sigma\,(\eta\,\rho)\Big\} \qquad (49)$$

when there are several gauges of wire on the line. It will be evident that x and z are correct only when they keep constant during the successive measurements.

On a perfect line x does keep constant, but the resistance z of the fault varies owing to the testing current which passes through it. Hence our first endeavour must be to eliminate this error *by employing as small a battery power as the sensibility of the testing arrangement during the measurement of I will allow of, by measuring with positive and negative currents, and by keeping the testing currents on as short a time as possible.*

The current which passes through the fault, when one and the same battery is employed for determining I, W, and w, is evidently greater when measuring I than when measuring W, and greater when measuring W than when measuring w. This difference will be greatest when the resistance of the fault is considerable, and it is situated much nearer to the distant than to the testing station, which may be recognised by the fact of the distant station being able to receive signals much better than the testing station. We can, however, determine the ratio of the electromotive forces so that the current passing through the fault shall be the same in each case.

The current passing through z is:

$$C_1=\frac{E}{x+z+\dfrac{x\,z}{L-x}} \text{ when measuring } w$$

$$C_2=\frac{E}{x+z+\dfrac{x\,z}{L-x+r}} \text{ when measuring } W$$

$$C_3=\frac{E}{x+z} \text{ when measuring } I$$

Hence in order to have $C_1=C_2=C_3$ we must take the electromotive forces in the following proportion :

$$E_1 : E_2 : E_3 :: \left\{x+z+\frac{xz}{L-z}\right\} : \left\{x+z+\frac{xz}{L-x+r}\right\} : \{x+z\}$$

In practice we may take $E_2=E_1$, so there only remains the ratio of $\frac{E_1}{E_3}$ to be determined. To do this we first ascertain W, w, and I roughly, in order to get some approximate values for x and z. This is best done by first taking the reading, using the whole E. M. F. available for testing. Namely, take first a reading of W with a positive current. Let this value be W'. Then reverse the battery and take a reading of W with negative current. Let this value be W''.

Then $$W=\frac{W'+W''}{2}$$ is sufficiently correct.

Similarly measure

$$w=\frac{w'+w''}{2}$$

Now reduce the E. M. F. of the testing battery in the proportion of 4 to 3, and take a reading of I with a positive current. Let this value be I'. Reverse the battery and take a reading of I with a negative current. Let this value be I''.

Then $I=\frac{I'+I''}{2}$ is sufficiently correct. From these rough values of W, w, and I calculate the approximate values of x and z, and thence the ratio $\frac{E_1}{E_3}$, which generally will be found to differ from the ratio $\frac{4}{3}$ used in the first experiment. Now make a second determination of W, w, and I, using electromotive forces which stand in the ratio $\frac{E_1}{E_3}$. For E_3 use no greater E. M. F. than is required to get accurate readings. Note, also, the deflections before and after measuring W and w ($a^{\circ\prime}$ and $a^{\circ\prime\prime}$), and before and after measuring I ($b^{\circ\prime}$ and $b^{\circ\prime\prime}$). Then $a^{\circ\prime}$ should $= a^{\circ\prime\prime}$ nearly, and be of the same sign; $b^{\circ\prime}$ should $= b^{\circ\prime\prime}$ nearly, and be of the same sign; b° should $>$ a° invariably; and a° should be of the same sign as b°. From these measured values (W' and W'', w' and w'', I' and I''), the correct values for W, w, and I can be calculated by the appropriate formulæ.

4. Now calculate x and z, employing the new values of W, w, and I. If they are found to correspond sufficiently with those ascertained before, they may be taken as correct. If, however, the difference is considerable, then a fresh ratio $\frac{E_1}{E_3}$ should be calculated with the new x and z, and with that ratio a fresh determination of W, w, and I should be made in exactly the same manner as before. From the new W, w, and I the true x is then to be calculated.

The following are simple criteria of accurate measurements:—

$I > W > w$ invariably.

$\frac{x}{L}$ positive and not greater than unity.

When a fault is quite close to the testing station, however, it may happen that x becomes negative on account of observation errors. After having ascertained the correct x, there will be no difficulty in calculating the right distance of the fault from the testing station, since the line is supposed to be highly insulated.

EXAMPLE.—On a single line 420 miles in length, and consisting throughout of No. 24 wire, there occurs imperfect communication due to a partial earth. The dry bulb readings of both the stations give 100° F. The fault occurs in the dry season, and is localised at noon, when it is known that, as a rule, the line has an insulation greater than 420 Ω per mile. L the total conduction resistance of the line, calculated from the gauge, and corrected for temperature, as well as directly measured, gives almost the same result:

$$L=4410 \text{ at } 80^\circ \text{ F.}$$

or

$$L=4623 \ ,, \ 100^\circ \text{ F.}$$

1*st* experiment:

$$W=\frac{W'+W''}{2}=\frac{4980+4700}{2}=4840 \quad E_2=40$$

$$w=\frac{w'+w''}{2}=\frac{4500+4300}{2}=4400 \quad E_1=40$$

$$I=\frac{I'+I''}{2}=\frac{5500+5000}{2}=5250 \quad E_3=30$$

Hence approximately, the resistance of the relay at the distant station, corrected for temperature, being 2500 ω

$$z=\sqrt{\frac{(5250-4840)\ (5250-4400)\ 2500}{4840-4400}}=1407$$

$$\therefore \qquad x=5250-1407=3843$$

We thus have

$$\frac{E_1}{E_3}=\frac{1407+3843+\dfrac{1407\times 3843}{4623-3843}}{1407+3843}=2{\cdot}3 \text{ nearly.}$$

Hence

2*d* Experiment:

$$\begin{array}{llll}
\begin{array}{l} 11^\circ\ Rt. \\ 10^\circ\ ,, \end{array} & \left\{\begin{array}{l} W'=4860 \\ W''=4654 \end{array}\right\} & \begin{array}{l} \text{means.} \\ 4757 \end{array} & E_2=20 \\
\begin{array}{l} 9^\circ\ ,, \\ 8^\circ\ ,, \end{array} & \left\{\begin{array}{l} w'=4490 \\ w''=4278 \end{array}\right\} & 4384 & E_1=20 \\
\begin{array}{l} 15^\circ\ ,, \\ 18^\circ\ ,, \end{array} & \left\{\begin{array}{l} I'=5250 \\ I''=4750 \end{array}\right\} & 5000 & E_3=9
\end{array}$$

In this case the results are sufficiently near together to allow of our taking the mean of the positive and negative readings.

Hence $$z=\sqrt{\frac{(5000-4757)(5000-4384)2500}{4757-4384}}=1002$$

$$\therefore \qquad x=5000-1002=3998$$

This value of x corresponds within 4 °/₀ with that first found, so that it may be accepted as the true value. Hence for the distance of the fault we have

$$n=\frac{3998}{11}=363 \text{ miles about.}$$

The wire was found off two posts and resting on the ground at 362½ miles from the testing station.

§ 5. Influence of leakage.—If a line, which contains a partial earth of considerable resistance (z), has such a low insulation (J per mile) that z cannot be neglected against the absolute corrected insulation (i) of the line, then, although the method of localisation must be exactly the same as before, the values of x and z obtained are not those we want. For x in this case is the distance of the resultant fault (in resistance) from the testing station, and z is the resistance of that resultant fault. If we suppose that the line in question is uniformly insulated, it is possible to find the correction.

Say that the values of x and z obtained from the observations are x' and z'.

Then by formulæ 22 and 23, we have

$$x'=\frac{ix+lz}{z+i}$$

and $$z'=\frac{iz}{i+z}$$

where l is the distance of the resultant fault (due to uniform leakage) of resistance i, and x the distance of the fault z: both distances measured in resistance from the testing station. x' and z' are found by observation. J, i, and l are known from previous experiments (*i.e.*, from the test records of the line). Hence z and x are expressed as follows:

$$z=\frac{i\,z'}{i-z'}$$

$$x=(1+\epsilon)\,x'-\epsilon\,l \qquad \ldots \qquad \ldots \qquad (50)$$

where

$$\epsilon=\frac{z}{i}$$

Substituting the value of x for w in formulæ 39 and 40, we have

$$n=\frac{1}{k}\left[(1+\epsilon)\left\{I-\sqrt{\frac{(I-W)\,(I-w)\,r}{(W-w)}}\right\}-\epsilon\,l\right] \qquad \ldots \qquad (51)$$

when the wire is of uniform gauge throughout the line; and

$$n=\Sigma(\eta)+\frac{1}{k}\left[(1+\epsilon)\left\{I-\sqrt{\frac{(I-W)(I-w)r}{W-w}}\right\}-\epsilon l-\Sigma(\eta\rho)\right] \quad (52)$$

when there are several gauges of wire on the line.

An example will make this clear.

Example.—On a single wire line during the monsoon months, in addition to the already great leakage owing to the unfavourable weather, a partial earth occurs which renders communication very imperfect. The length of the line is 250 miles, and it consists of No. 24 wire throughout.

The localisation test gives

$$x'=1456$$

and

$$Z'=\;\;518$$

Further, we suppose that the line is uniformly insulated, and therefore

$$l=1312{\cdot}5$$

The corrected insulation of the line, taken from tests made during the preceding week, is 0·42 Ω per mile.

Thus probable $i = \dfrac{0{\cdot}42\,\Omega}{250} = 1680\,\omega.$

Thus we have $z = \dfrac{518 \times 1680}{1680 - 518} = 749$

and
$$x = \left(1 + \frac{749}{1680}\right) 1456 - \frac{749 \times 1312}{1680}$$
$$= 1520\ \omega.$$

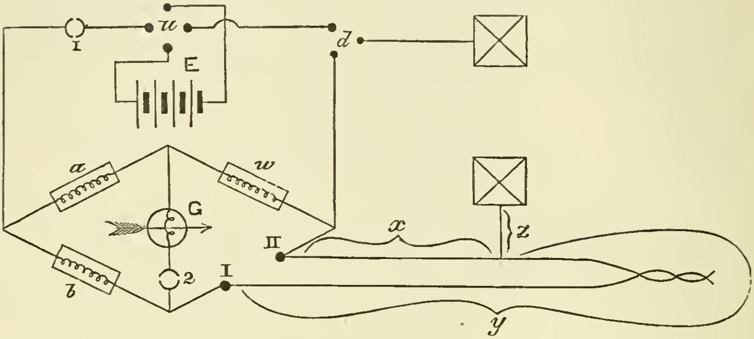
Hence, the probable distance of the fault is
$$n = \frac{1520}{10{\cdot}5}$$
$$= 145 \text{ miles about.}$$

The wire was found resting on the bracket at 146 miles from the testing station.

§ 6. Localisation of an "earth" by the Loop Method. —This is undoubtedly the most convenient and accurate method of localising an "earth." It requires a second wire to be available between the two stations which are connected by the faulty wire. In India this condition is generally fulfilled, and under such circumstances no other method should be employed for localising an earth. The faulty wire is to be connected directly with the second wire at the distant station, forming a metallic loop of which the two ends are at the disposal of the testing officer.

The principle of the method is to determine by measurement the value of the ratio between the resistances of the two sections of the loop included respectively between the one end of the loop and the fault, and the fault and the other end of the loop. Either of the testing arrangements—Bridge or Differential Galvanometer—may of course be employed for determining that ratio. Fig. 11 gives the diagram when the Bridge is used.

Fig. 11.



The metallic junction between the two lines at the distant station should be carefully insulated from the ground. We will at first suppose that, except at the fault, the loop is perfectly insulated. When there is balance in G, we have, with earth on Bridge,[1]

$$\frac{a}{b} = \frac{w + x}{y}$$

Further

$$x + y = W$$

either known from the test records, or better measured at the time with earth off Bridge. From these two equations we have at once

$$x = \frac{aW - bw}{a + b} \qquad \ldots \qquad \ldots \qquad (53)$$

---

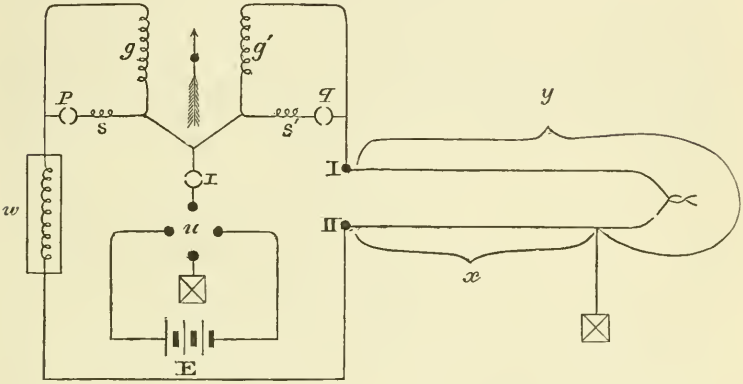
[1] x must be always smaller than y. In practice we make $a = b$, and connect the ends of the two lines to the terminals I and II of the Bridge. If we cannot get balance, even when $w = o$, we must interchange the two wires between the terminals I and II. Clearly if the two lines are approximately of the same absolute conduction resistance, the faulty line must be connected to II, and the good line to I.

When $a = b$, as is generally the case, this formula becomes

$$x = \frac{W - w}{2} \quad \dots \quad \dots \quad \dots \quad (54)$$

Fig. 12 gives the diagram when the Differential Galvanometer is used.

Fig. 12.



It is in this case also assumed that except at the fault the loop has no perceptible leakage. If balance is obtained without using the shunts,[1] then we have

$$x + w = y$$

the two differential coils being supposed to have equal magnetic effects.

Further $\quad W = x + y$

Thus $\quad x = \frac{W - w}{2} \quad \dots \quad \dots \quad (54)$

---

[1] Shunts will not generally be required in this case, but if they should be, the formula expressing x can be easily arrived at.

Substituting the value of x for w in formulæ (39) and (40), we have

$$n = \frac{W - w}{2\,k} \quad \ldots \quad \ldots \quad \ldots \quad (55)$$

when the wire is of the same gauge throughout the line; and

$$n = \Sigma\,(\eta) + \frac{1}{k}\left\{\frac{W - w}{2} - \Sigma\,(\eta\,\rho)\right\} \ldots \quad (56)$$

when there are several gauges of wire on the line.

§ 7. Advantages of the Loop Method.—So long as the loop contains only *one* fault, the localisation of the fault is quite independent of its resistance. Hence variations of z, arising either in itself or owing to the passage of the test currents, cannot influence the accuracy of the result. Further, any natural current that may exist in the loop at the time of testing cannot have any influence on the accuracy of the result. For the E. M. F. of such a natural current can do nothing more than either add to or subtract from the E. M. F. of the testing battery. In other words, tests with positive and negative currents should give exactly the same results, or at least results no more different than can be explained by ordinary observation errors, or actual variations of the resistance of the loop. If the results obtained with positive and negative test currents are different, we conclude that more than one fault exists in the loop. This is in fact generally the case in practice, especially when localising a partial earth. *If the loop test, with or without earth on the testing battery, gives different results with positive and negative test currents, then the loop in question has at least two faults.*

How this effect is to be taken into account will form the subject of the next paragraph.

§ 8. Correction for the Loop Method.—Formula (54) was developed under the supposition that only *one* fault (z) existed in the loop. This supposition is, however, only fulfilled when the fault in question has a resistance either approximating to zero, or more generally so small as to be neglected against the absolute insulation of the loop. If this is not the case, then the loop must be considered to have two faults, *i.e.*, the one due to leakage along the whole loop (without z), the resistance of which (i) is the absolute corrected insulation of the loop, and the other is the actual fault (z) which has to be localised. Hence by formula (54) we do not localise the fault (z) but the resultant of i and z, the resistance of which is $\frac{i\,z}{i+z}$.

In this case we have[1]

$$x = (1 + \epsilon)\,\frac{a\,W - b\,w}{a + b} - \epsilon\,l$$

---

[1] We have

$$x' = \frac{a\,W - b\,w}{a + b}$$

the distance of the resultant fault $\frac{i\,z}{i+z}$ from the testing station. According to the definition of the resultant fault we have

$$\frac{x' - x}{z} = \frac{l - x'}{i}$$

$$\therefore \qquad x = x'\left(1 + \frac{z}{i}\right) - \frac{z}{i}\,l$$

Putting $\frac{z}{i} = \epsilon$ and substituting for x' its value, we get

$$x = (1 + \epsilon)\frac{a\,W - b\,w}{a + b} - \epsilon\,l$$

which becomes

$$x = (1 = \epsilon)\ \frac{W - w}{2} - \epsilon\, l \qquad \dots \qquad \dots \qquad (57)$$

when $a = b$.

This latter formula represents also that to be employed when an ordinary Differential Galvanometer is used. Substituting the value of x for w in formulæ (39) and (40), we have

$$n = \frac{1}{k}\left\{(1 + \epsilon)\ \frac{W - w}{2} - \epsilon\, l\right\} \qquad \dots \qquad \dots \qquad (58)$$

when the wire is of the same gauge throughout the line; and

$$n = \Sigma\,(\eta) + \frac{1}{k}\left\{(1 + \epsilon)\ \frac{W - w}{2}\,\epsilon\, l - \Sigma\,(\eta\,\rho)\right\} \quad (59)$$

when there are several gauges of wire on the line.

In order to be able to calculate x by formula (57) we must know the value of $\epsilon = \frac{z}{i}$ and that of l. The best method for getting the most correct value of $\epsilon = \frac{z}{i}$ is by measuring the conduction resistance of the loop *without having earth on the testing battery.* In this case the current which passes through the two faults i and z is the same, and hence the ratio ϵ, whatever it may have been during the localisation test (determination of x'), cannot be affected by this second test. Besides this method of determining ϵ is also more convenient, since it gives us, without much alteration of the connections in the testing apparatus, a simple criterion whether the correction is required or not. If we call $R = L' + L''$ the true conduction resistance of the loop, and W the measured conduction resistance of the loop (no earth to battery), then

$$1+\epsilon=\frac{(R-W)\,(i+l-x')}{(l-x')^2}\text{[1]} \quad \cdots \quad (60)$$

where x' is the value found by the localisation test, and $1+\epsilon$ can be calculated if R, l, and i are known. If we find that $W=R$, then we conclude that $i=\infty$, *i.e.*, $\epsilon=0$, or no correction is necessary. Hence $R-W$ is a measure of the necessity of the correction. As far as L' and L'' are concerned, we know their values either from previous loop tests (when insulation was high), or from calculation. In the above formula it must, however, not be forgotten to invariably correct L' and L'' for temperature. R, unless a partial discontinuity exists in the line, is always sufficiently accurately known. With respect to the values of i and l we are not so fortunate, because they are subject to great variations on overland lines. A direct determination of them at the time of the fault test is, however, impossible, and all that we can do is to get the most probable values for l and i. Suppose at first that l and i of the loop had both been ascertained just before

---

[1] $$W=R-(l-x)+\frac{(l-x)\,(z+i)}{l-x+z+i}$$

$$\therefore \qquad i+z=\left(\frac{l-x}{R-W}-1\right)(l-x)$$

Divide by i, and put $\frac{z}{i}=\epsilon$

$$1+\epsilon=\left(\frac{l-x}{R-W}-1\right)\frac{l-x}{z}$$

but by formula (50) $x=(1+\epsilon)x'-\epsilon l$ which, substituted in the expression for $1+\epsilon$, gives

$$1+\epsilon=\frac{(R-W)\,(i+l-x')}{(l-x')^2}$$

the fault z occurred in one of the two lines. Further, that from that moment to the time the fault occurred the electrical condition of the two lines (except the occurrence of the fault z) had kept unchanged, then we might at once introduce l and i in the formula for $1+\epsilon$. Such a proceeding would be perfectly right when dealing with a perfect cable, which has become slightly faulty, but in the case of overland lines it would be wrong.

The following procedure is to be adopted. Determine the electrical condition of the perfect line, *i.e.*, by circuit, conduction, and insulation tests. From these three measurements find l'' and i'' (formulæ 18 and 16).

Then put $i' = a\,i''$

and $l' = b\,l''$

Where a and b are coefficients, the probable values of which are to be computed from the regular test records, *i.e.*, i' and l' would be most probably the values which would have been found at the time of testing, if z had not existed in the line.

$$\left.\begin{aligned} \text{Hence}\qquad i &= \frac{i'\,i''}{i'+i''} \\ \text{and}\qquad l &= \frac{l'\,i''+l''\,i'}{i'+i''} \end{aligned}\right\}\ \text{formulæ 22 and 23.}$$

An example will make this clear.

Example.—On a line 300 miles in length communication becomes imperfect owing to a partial earth. The localisation by the loop method is commenced at 8 hours. Parallel with this defective line runs another of the same length, which remains perfect. Both the lines consist of No. 24 wire, and the perfect line is supported on Prussian pattern insulators, while the other is on Half-hoods. Previous tests of these lines have given the average mileage resistance = 10·5 ohms at 80° F. At the time of test the temperature at the testing station is 83°. Correction of R for temperature is therefore not necessary.

Thus $$R = 6300 \text{ ohms at } 83^\circ \text{ F.}$$

Now measuring the electrical condition of the perfect line, it is found that

$$l'' = 1000$$

and $$i'' = 10000$$

Then making the loop test with earth on battery,

$$w = 503$$

and making the loop test *without* earth on battery,

$$W = 5400$$

Hence $$R - W = 6300 - 5400 = 900$$

which shows that the correction is required. After this measure again the electrical condition of the perfect line, when

$$l'' = 1020$$

and $$i'' = 10500$$

Further comparing the electrical condition of the two lines, it is found from the test records that :

$$\left.\begin{aligned} i'' &= 15000 \\ i' &= 7800 \\ i'' &= 9000 \\ i' &= 4500 \\ i'' &= 12000 \\ i' &= 7000 \end{aligned}\right\} \text{ at about 8 hours.}$$

Further

$$\left.\begin{aligned} l'' &= 800 \\ l' &= 850 \\ l'' &= 950 \\ l' &= 900 \\ l'' &= 1040 \\ l' &= 1080 \end{aligned}\right\} \text{ ditto.}$$

Then

$$\frac{i'}{i''}=a=\frac{6433{\cdot}3}{12000}=0{\cdot}536$$

$$\frac{l'}{l''}=b=\frac{943{\cdot}3}{930}=1{\cdot}014$$

Hence the most probable values of l' and i' are

$$i'=0{\cdot}536\times10250=5494$$

and $l'=1{\cdot}014\times\ 1010=1024$

Thus

$$i=\frac{i'\,i''}{i'+i''}=\frac{5494\times10250}{5494+10250}=3577$$

and $$l=\frac{l'\,i''+l''\,i'}{i'+i''}=\frac{1024\times10250+(6300-1010)\,594}{5494+10250}=2526$$

Therefore

$$1+\epsilon=\frac{(6300-5400)\,(3577+2526-503)}{(2526-503)^2}=1{\cdot}23$$

Thus

$$x=1{\cdot}23\times503-2526\times0{\cdot}23=38$$

Hence

$n=\frac{38}{10{\cdot}5}=3\frac{1}{2}$ miles about from the testing station.

§ 9. Influence of natural currents.—If only one fault exists, then clearly whatever may be the E. M. F. between that fault and the distant earth, it cannot influence the balance condition, for in this case the E. M. F. of the natural current is actually situated in the battery branch of the bridge. If the E. M. F. of the testing battery is E and that of the natural current e, then testing with reversed currents, we have $E+e$ in the one case, and $E-e$ in the other, *i.e.* affecting, if e is large enough, only the sensitiveness of the method but not its correctness. In such a case measurements with positive and negative test currents should give the same result. But if a line contains two faults, in one or both of which, *i.e.*, between the wire and the earth, there exists an E. M. F., then the case is different. In this case the results obtained with + and − test currents may be different, and the question only remains how to get from the two different results the correct reading. Suppose that in the fault i an E. M. F. e exists, and in z another e', then clearly the result would be a current of given strength in the galvanometer. Now imagine these two E. M. FS. removed and replaced by another E. M. F. which is inserted somewhere in the loop, and sends exactly the same current through the test galvanometer as the two actually existing E. M. FS. do. Then the elimination of that unknown E. M. F. (which may be called the resultant of e and e') can be done in exactly the same way as is given in pp. 16 and 34.

The fact of getting different readings with + and − test currents, and that when putting the testing apparatus to earth without a testing battery in circuit after obtaining balance, a natural current is observed to exist in the loop, gives invariably a criterion for the necessity of using the correct formula (57). For otherwise no such current could be observed after balance had been obtained.

As a general rule the influence of natural currents on the results by loop tests will however be small. For not only are the E. M. FS. which produce natural currents at ordinary times very small (the fraction of a volt), but the resistance through which they act (i and z) are also comparatively high. For if this were not the case, say for instance z is very small in comparison with i, then the method reverts to a loop test with *one* fault only, when as stated before natural currents cannot influence the balance equation.

XI. *Localisation of Contacts.*—We shall at first suppose that the two lines are in contact at *one* point only. Let the absolute conduction resistance of the No. I. line be L', of the No. II. line L'', and the resistance of the contact be z. Then execute the following two tests:—

Firstly. Measure the resistance W of the two lines when their ends at the distant station are *insulated* (from one another as well as from the earth).

Secondly. Measure the resistance w of the two lines when their ends at the distant station are directly *connected* together (but still insulated from the earth).

Further, let the resistance between the contact and the testing station along the No. I. line be x', and along the No. II. line x'', then clearly we have

$$W = x' + x'' + z$$

and
$$w = x' + x'' + \frac{z\,(L' - x' + L'' - x'')}{z + L' - x' + L'' - x''}$$

Putting $x' + x'' = X$

and $L' + L'' = R$

Then $W = X + z$

and
$$w = X + \frac{z\,(R - X)}{z + R - X}$$

From which we have

$$X = w - \sqrt{(R - w)\,(W - w)} \quad \ldots \quad (61)$$

$$z = W - w + \sqrt{(R - w)\,(W - w)}$$

From the formula for X, the distance n of the fault can be easily computed. Suppose that each line consists of a uniform gauge throughout its length, the resistance per mile of the No. I. line being k', and of the No. II. line k''; and that the two lines are of equal length between the contact and the testing station.

Then we have

$$X = x' + x'' = (k' + k'')\, n$$

and therefore

$$n = \frac{w - \sqrt{(R - w)\,(W - w)}}{k' + k''} \quad \ldots \quad (62)$$

If the two lines in contact are not of equal length between the contact and the testing station, as for instance when one of the lines branches off in form of a diversion, then, if we call the total length of this d, we have

$$X = x' + x'' = n\,k' + (n + d)\,k''$$

supposing the loop to exist in the No. II. line.

$$\text{Therefore } n = \frac{X - d\,k''}{k' + k''}$$

$$= \frac{w - \sqrt{(R - w)\,(W - w)} - d\,k'}{k' + k''} \quad (63)$$

When the two lines consist of the same gauge, or $k' = k'' = k$,

$$n = \frac{w - \sqrt{(R - w)\,(W - w)}}{2\,k} \text{(lines of equal length)} \quad (64)$$

and

$$n^1 = \frac{w - \sqrt{(R - w)\,(W - w)}}{2\,r} - \frac{d}{2} \text{ (lines of unequal length)} \quad (65)$$

It will be seen that so long as $z > o$, $W > w$. If the two measurements give $W = w$, we conclude that the contact offers no perceptible resistance, and the general formulæ given above assume the following simpler forms :—

---

[1] This n is then of course the distance along the shorter line.

$$n = \frac{w}{k' + k''} \text{ (lines of equal length but different gauges)} \quad (66)$$

$$n = \frac{w - d\,k''}{k' + k''} \text{ (lines of unequal length and different gauges)} \quad (67)$$

$$n = \frac{w}{2\,k} \text{ (lines of equal length and the same gauge)} \quad (68)$$

$$n = \frac{w}{2\,k} - \frac{d}{2} \text{ (lines of unequal length but the same gauge)} \quad (69)$$

§ 1. Case of several gauges of wire in the lines.—When the lines in contact contain several different gauges, there will be no difficulty in computing the distance n provided of course that the gauges, and their order and lengths, are known. It must only be remembered that a point p has to be selected nearer to the testing station than the contact, which fulfils the condition that between it and the contact the gauge in both lines keeps constant. We thus have

$$n = \Sigma\,(\eta') + \frac{w - \sqrt{(R - w)\,(W - w)} - \Sigma\,\{(\eta'\rho') + \Sigma(\eta''\rho'')\}}{k' + k''} \quad (70)$$

where n is the distance in miles from the testing station along the shorter line.

Example.—Two lines, Nos. I. and II., are in contact.

No. I. Miles.	I. W. G.	Resistance at 80° F.	No. II. Miles.	I. W. G.	Resistance at 80° F.
100	24	1050	50	50	252
50	50	252	100	24	1050
20	36	140	80	36	560
40	16	630	90	32	708
150	24	1575	...	...	...
360		3647	320		2570

The diversion exists in the No. I. line, namely, this line at the end of the No. 36 wire branches off (total length of loop is 40 miles), and returns at the beginning of the No. 24 wire.

$$\left.\begin{aligned} W &= 5942 \\ w &= 5608 \end{aligned}\right\} \text{at } 80° \text{ F.}$$

Further, $R = L' + L'' = 3647 + 2570 = 6217$ at 80° F.

Hence by formula (61)

$$X = 5140$$

and

$$z = 802$$

Now if we select a point p in the No. II. line 230 miles distant from the testing station, *i.e.*, where the No. 32 wire joins the No. 36 wire, we have a resistance of 1862 up to that point.

A point p distant 230 miles from the testing station (not including 40 miles of loop) would be situated on the No. I. line in the No. 24 wire, namely, 60 miles further away from the testing station than the junction between the No. 16 and No. 24 wires in the No. I. line, and therefore the resistance up to this point would be 2702. The sum of these two resistances is $1862 + 2702 = 4564$, which is smaller than $X = 5140$. Hence the point p is correctly selected.

Thus

$$\frac{5140 - 4564}{10{\cdot}5 + 7{\cdot}87} = \frac{576}{18{\cdot}37} = 31\tfrac{1}{4} \text{ miles about}$$

as the distance of the contact from the point p, or $n = 230 + 31\frac{1}{4} = 261\frac{1}{4}$ miles is the distance of the contact from the testing station along the shortest line. It may assist the tester to draw a diagram of the two lines in contact, showing the length and resistance of the several gauges. It will then be always easy to select the point p.

§ 2. Influence of leakage on the localisation of a contact.—Unless the resistance of a contact is not absolutely zero (metallic), leakage between the two wires must necessarily influence the localisation test. How large this influence may be will depend on the ratio between the resistance of the contact to be localised and the contact due to leakage. If we call i' the corrected absolute insulation resistance of the No. I. line, and i'' that of the No. II. line, then the resistance of the contact due to leakage only will be

$$i=i'+i''$$

If now another contact occurs with resistance z, then the localisation test must give the position and resistance of the resultant contact $\frac{i\,z}{i+z}$. If we put $\frac{z}{i}=\epsilon$, formula (61) becomes

$$X=\{w-\sqrt{(R-w)(W-w)}\}(1+\epsilon)-\epsilon\,l \quad \ldots \quad (71)$$[1]

and whether the correction is required or not will depend on the value of $\epsilon=\frac{z}{i}$ only.

$l=l'+l''$ is the resistance of the two lines in contact between the testing station and that point of the two lines where we may imagine that the leakage acts (i).

We can always find ϵ, for if z' = resistance of resultant contact, then

$$\frac{i\,z}{i+z}=z'$$

Whence $$\epsilon=\frac{z'}{i-z'}$$

$i=i'+i''$, as well as $l=l'+l''$, are known from previous tests. The means of such tests are only to be taken as were taken at about the same hour of the day and season of the year as when the localisation test was made. The most general formula for the localisation of a contact thus becomes:

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[1] By l' we will designate the resistance from the testing station to the contact (i) along the No. I. line, and by l'' along the No. II. line. A similar meaning will attach to x' and x'' with respect to the position

$$n=\Sigma(\eta')+\frac{\{w\sqrt{(R-w)(W-w)}\}(1+\epsilon)-\epsilon l-\{\Sigma(\eta'\rho')+\Sigma(\eta''\rho'')\}}{k^1+k''} \quad (72)$$

Example.—Between two lines, each 300 miles in length, occurs a contact. Both lines consist of No. 24 wire throughout. By direct measurement we get, at 9 hours in the month of August, raining,

$$\left.\begin{aligned} W &= 2600 \\ w &= 2400 \end{aligned}\right\} \text{at an average temperature of } 80^\circ \text{ F.}$$

---

of the contact (z), and to v' and v'' with respect to the resultant contact $\frac{i\,z}{i+z}$. According to equation 22.

$$v'=\frac{l'z+x'i}{i+z}$$

$$v''=\frac{l''z+x''i}{i+z}$$

$$\therefore \qquad v'+v''=\frac{(l'+l'')\,z+(x'+x'')\,i}{i+z}$$

Put $\quad l'+l''=l$

$$x'+x''=X$$

and $\quad v'+v''=v$

$$\therefore \qquad v=\frac{l\,z-X\,i}{i+z}=\frac{\epsilon\,l+X}{1+\epsilon}$$

but v is evidently the value found by direct measurement (formula 61). Thus we have

$$X=\{w-\sqrt{(R-w)\,(W-w)}\}(1+\epsilon)-\epsilon\,l$$

The value of X, we may also write

$$x=v\,(1+\epsilon)-l\epsilon=v+\epsilon\,(v-l)$$

Thus $X > v$ if $v > l$, and $X < v$ if $v < l$; $v=l$ can only be obtained when either $i=\infty$, or $z=0$, in both of which cases $\epsilon=0$.

Further, from the test records, or by calculation, we find

$$R = 6300 \text{ at } 80^\circ \text{ F.}$$

Then we get

$$\left.\begin{aligned} v &= 1517 \\ \text{and } z' = \frac{iz}{i+z} &= 1083 \end{aligned}\right\} \text{ohms.}$$

From the test records, taking only measurements that were made between 8 and 10 hours in the month of August (when raining) give

$$J' = 0{\cdot}72\ \Omega \text{ mean per mile No. I. line}$$

$$J'' = 0{\cdot}48\ \Omega \quad \text{,,} \quad \text{II. line}$$

$$\left.\begin{aligned} l' &= 1550 \\ l'' &= 1660 \end{aligned}\right\} \text{Resultant fault almost in the middle of the conductor in both lines.}$$

Thus $$i = i' + i'' = \frac{0{\cdot}72 + 0{\cdot}48}{300}\ \Omega = 4000\ \omega$$

and $$l = l' + l'' = 1550 + 1600 = 3150\ \omega$$

Hence $$\epsilon = \frac{z}{i} = \frac{1083}{4000 - 1083} = 0{\cdot}21$$

or $$X = 1517 \times 1{\cdot}21 - 3150 \times 0{\cdot}21 = 1174\ \omega$$

$$\therefore \qquad n = \frac{1174}{21} = 56 \text{ miles about.}$$

It was found that the contact was caused by a dead snake twisted round the wires at about the 56th mile, which during the rain caused considerable cross leakage.

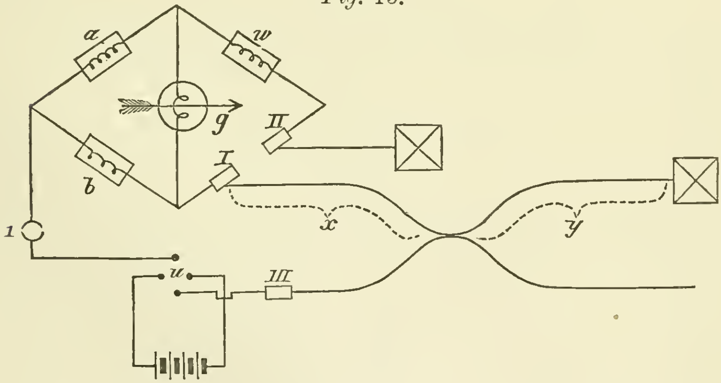
§ 3. Influence of natural currents on the localisation of contacts.—If the two lines are perfectly insulated, and if the contact is metallic ($z = o$), then clearly no natural current can exist in the loop, and the localisation is reduced to the simple measurement of a wire resistance.

If, however, the two lines are not perfectly insulated, and the contact to be localised is *not* metallic ($z > 0$), then there may be a natural current in the loop. Further, it will then be observed that this natural current is affected by the test currents, *i.e.*, by the polarisation of the contact z, as well as of that due to the general leakage of the two lines, and therefore the usual precaution of testing must be used. Whatever may be the cause of the natural current in the loop, it is clear that its effects can be eliminated by taking readings with reversed test currents.

It must, however, be remembered that only those successive positive and negative readings can be used for which the natural current has not sensibly altered its direction or magnitude. Hence before and after each reading the sign and magnitude of the natural current should be ascertained.

§ 4. Localisation of "contacts" by methods that eliminate the resistance of the contact.

Fig. 13.



1*st* Case. There are only two wires on the line, namely, those that are in contact with one another.

Connect one of the lines, the distant end of which is to be put direct to earth, to the Bridge at the point I., and the other line, the distant end of which is to be insulated to one pole of the testing battery, the other pole of which is to the Bridge. Put earth on at II., and make $a = b$. If we cannot get balance thus, we must put the earth on at I., and the line on at II. Then at balance, with the connections as shown in the diagram,

$$a\,x = b\,(w + y)$$

But $x + y = L$, known from the regular tests or computed,

$$\therefore \qquad x = \frac{b}{a+b}\,(L + w)$$

when $a = b$

we have
$$x = \frac{L + w}{2} \qquad \dots \qquad \dots \qquad (73)$$

Substituting the value of x for w in formulæ (39) and (40), we have

$$n = \frac{L + w}{2\,k} \qquad \dots \qquad \dots \qquad (74)$$

when the wire is of uniform gauge throughout the line; and

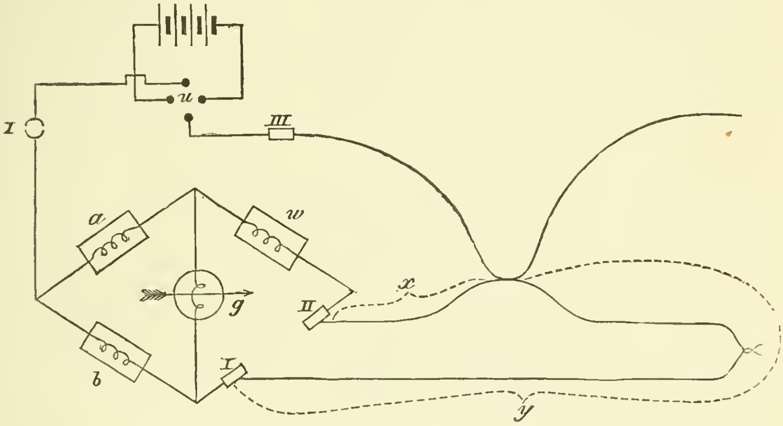
$$n = \Sigma\,(\eta) + \frac{1}{k}\left\{\frac{L + w}{2} - \Sigma\,(\eta\,\rho)\right\} \quad \dots \qquad (75)$$

when there are several gauges of wire in the line.

It is clear that the results obtained by this method will be influenced by leakage due to imperfect insulation, and also by natural currents. The effects of the latter can be neutralised by testing with positive and negative currents, and calculating the results by the appropriate formulæ; but the effects of the former cannot be eliminated, and therefore this method of localisation should not be employed when the insulation is low.

2*d* Case.—There is a good wire available in addition to the two wires that are in contact with one another. Loop the good wire with one of the faulty wires at the distant station, and insulate the other faulty wire. Connect the good wire to the terminal I or II of the Bridge, and the faulty wire, with which the good wire is looped at the distant station, to the terminal II or I. Connect the other faulty wire to one pole of the testing battery.

Fig. 14.



Then at balance

$$a\, y = b\, (w + x)$$

and by a loop test we can find

$$x + y = W$$

$$\therefore \qquad x = \frac{a\, W - b\, w}{a + b}$$

When $a = b$

$$x = \frac{W - w}{2} \qquad \ldots \qquad \ldots \qquad (76)$$

Substituting the value of x for w in formulæ (39) and (40), we have

$$n = \frac{W - w}{2\,k} \quad \ldots \quad \ldots \quad (77)$$

when the wire is of the same gauge throughout the line ;

$$n = \Sigma\,(\eta) + \frac{1}{k}\left\{\frac{W - w}{2} - \Sigma\,(\eta\,\rho)\right\} \ldots \quad (78)$$

and when there are several gauges of wire on the line. Natural currents will have no influence on the results obtained by this method ; and the effects of imperfect insulation will be reduced to a minimum. However, allowance can be made for imperfect insulation by means of formulæ precisely similar to formulæ 58 and 59.

XII. *General Rules Regarding the Localisation of Faults.*

1. The methods of localising faults as given in the foregoing include only those which involve tests made by one and the same station. At present the testing stations in India are comparatively few, and they are therefore at great distances from each other, so that the case of a fault being localised by two testing stations rarely happens in practice. In case, however, one and the same fault is localised by two testing stations, then the most probable position of the fault should be computed from the two results. Further formulæ containing tests of a faulty line made from the two ends of the line can be easily prepared by any one conversant with the subject.

2. Before localising a fault, it is necessary to know by qualitive tests to which class the fault belongs, *i.e.*, whether it is a discontinuity, earth, or contact.

A contact is distinguished at once from the other two classes by the signals sent on one line being received on another line. In order to discover a partial contact, adjust the relay on the one line as sensitively as possible, and then send a permanent beat on the other line. This permanent beat will then be received as a permanent beat on the sensitively adjusted relay. Or a still more sensitive method is to watch the indicator needle (placed in its most sensitive position) of the relay on the one line while giving a permanent beat on the other line. If during that permanent beat the needle of the indicator remains permanently deflected, then the two lines are in contact, although the contact may offer such a high resistance that the ordinary relay would not show it. If the deflection of the needle is not permanent during a permanent beat on the line, but indicates a transient current in one direction at the beginning of the permanent beat, and a transient current in the reverse direction at the end of the permanent beat, then we conclude that the two lines act inductively on each other. Well-insulated wires running in close proximity to each other for a considerable distance will invariably exhibit this inductive action, which must not be confounded with that due to contact, as often has been done. The inductive action between Telegraph lines becomes most serious on the long main routes. It cannot be entirely eliminated, but only increased by using on the one hand as small an E. M. F. for sending as can be safely employed, and on the other hand by using those wires for through traffic which are placed at the greatest distance from each other. In the future construction of lines this influence should be taken into account when determining the distance of the wires from each other.

As a general rule the distinction between a "discontinuity" and an "earth" is also very simple, only in some particular cases it may become difficult to ascertain the true nature of the fault.

A total "discontinuity" must invariably show itself by the measured conduction or circuit resistances having considerably increased, *i.e.* far more than can be explained by other causes; as, for instance, an increase of temperature along the line. On the other hand, an "earth" must invariably show itself by the measured conduction or circuit resistance; or, better still, the measured insulation, showing a considerable decrease. The difference between the two kinds of faults, "discontinuity" and "earth," becomes more and more marked as the resistance of the "discontinuity" increases and the resistance of the "earth" decreases, and becomes perfectly prominent in the case of a "total discontinuity" and a "dead earth." But in the case of a discontinuity with earth, then the simple criterion as given above fails. If a second line is at our disposal, then we measure the resistance of the loop without having earth on the testing battery. If this test agrees sufficiently with the known resistance of the loop, the fault must be earth *without* discontinuity. If the measured resistance of the loop is much higher than its known resistance, the fault must be discontinuity *with* earth. For instance, say the wire actually breaks, and that the end of the broken wire on the side of the testing station is in contact with earth, while the other end is either perfectly or imperfectly insulated from the ground, then the loop test would show this at once. There is a case left, however, in which even this mode of distinction would prove insufficient.

For instance, say that both ends of the break are in perfect contact with the ground; then clearly the measured resistance of the loop would correspond with its known resistance. In this case, however, we may be sure to have a strong natural current in the loop due to a polarisation of the two earth-contacts by the test current. In case of a wire being intact, and having only a dead earth, such natural currents could not be observed.

If there is no second wire available, then in order to know whether imperfect communication is due to earth without discontinuity, or to a discontinuity with earth, we can do nothing else but execute the three tests, circuit, conduction, and insulation. Then calculate by formula (17) the value of L. If that calculated value is much higher than the known one, we have clearly to do with a partial discontinuity. If a total interruption is due to the breaking of the wire, it is clear that on arrangement, except the repair of the fault, can bring the line into work again. If, however, the total interruption is due to a dead earth, the use of more sensitive receiving instruments, an increase of the signalling battery, and a polarisation of the fault by a copper current, may give a chance of imperfect communication.

3. A total disconnection is invariably to be localised by a *capacity test*, supplemented if necessary by an *insulation test*. It is advisable to compare the capacities of all the lines in a testing office with the capacity of a condenser ; or if one is not available, with the capacity of the best insulated line.

4. A break which is in contact with earth *cannot* be accurately localised. Only the maximum distance is found by the localisation test.

5. A break, both ends of which are in perfect contact with the ground, can be localised by the loop method.

6. An earth on multiple lines must always be localised by the loop method.

7. The tester, under all circumstances, should know the quantitative probable error inherent in his test results, in order that he may be able to say within what two limits the fault in question is surely to be found.

8. In case of a fault occurring of any kind, the testing station, as well as the distant station, should both satisfy themselves by the requisite experiments that the fault is not in the offices, but on the lines.

9. The man starting to repair a fault must receive full instructions as to the nature and position of the fault. He should be instructed to travel with the utmost despatch to the point which indicates the minimum distance of the fault; and thence to inspect the line most carefully and minutely to the point indicating the maximum distance of the fault.

10. The line-men should be ordered to invariably bring back with them any objects removed from the line that may prove of interest or utility; *e.g.*, broken insulators, defective joints that have been cut out, the ends of a wire that has been found broken, bits of wire that caused contact, &c.; and these should be kept for examination by inspecting officers when on tour. Many useful indications of the causes of faults may be thus acquired.

XIII. *Recording of Fault Tests.*—Fault tests are to be recorded in the *Test Sheets* in red ink, after the entries of the regular tests. The actual observations made must be given, as well as an outline of the calculations by means of which the results have been obtained; and the following particulars must be added:—

Nature of fault.
Place localised.
Place found.
Cause of fault.
Duration.

The nature and locality of all faults should be noted by superintendents in their *Abstract of Tests,* as this information will be of the utmost value to them in showing which are the weakest points of their lines.

APPENDIX VII.

INDIAN TELEGRAPH IRON WIRE GAUGE.

Gauge.	Weight in lbs., per			Diameter in $\frac{1}{1000}$ inch.	Area of section in $\frac{1}{10000}$ sq. inch.	Breaking strain in lbs.	Resistance per mile in ohms at 80° F.	Ratio of the resistance in terms of No. 50 wire.
No.	Mile.	Yard.	Foot.					
1	25	·0142	·0047	42	14	83	252·00	50·000
2	50	·0284	·0095	60	28	167	126·00	25·000
3	75	·0426	·0142	75	43	250	84·00	16·667
4	100	·0568	·0189	85	57	333	63·00	12·500
5	125	·0710	·0237	95	71	417	50·40	10·000
6	150	·0852	·0284	104	85	500	42·00	8·333
7	175	·0994	·0331	112	99	583	36·00	7·143
8	200	·1136	·0379	120	114	697	31·50	6·250
9	225	·1278	·0426	127	128	750	28·00	5·556
10	250	·1420	·0473	134	142	833	25·20	5·000
11	275	·1562	·0521	140	156	917	22·91	4·545
12	300	·1705	·0568	147	170	1000	21·00	4·167
13	325	·1847	·0616	153	184	1083	19·38	3·846
14	350	·1989	·0663	159	198	1167	18·00	3·572
15	375	·2131	·0710	166	213	1250	16·80	3·334
16	400	·2273	·0758	170	227	1333	15·75	3·125
17	425	·2415	·0805	175	241	1417	14·82	2·941
18	450	·2557	·0852	180	255	1500	14·00	2·778
19	475	·2699	·0900	185	270	1583	13·26	2·632
20	500	·2841	·0947	190	284	1667	12·60	2·500
21	525	·2983	·0994	195	298	1750	12·00	2·381
22	550	·3125	·1042	200	312	1833	11·45	2·273
23	575	·3267	·1089	204	326	1917	10·96	2·174
24	600	·3409	·1136	208	341	2000	10·50	2·084
25	625	·3551	·1184	212	355	2083	10·08	2·000
26	650	·3693	·1231	217	369	2167	9·78	1·923
27	675	·3835	·1278	221	383	2250	9·33	1·852
28	700	·3977	·1326	225	397	2333	9·00	1·786
29	725	·4119	·1373	229	412	2417	8·67	1·724
30	750	·4261	·1420	233	426	2500	8·40	1·667
31	775	·4403	·1468	237	440	2583	8·13	1·613
32	800	·4545	·1515	240	454	2667	7·87	1·563
33	825	·4687	·1562	244	468	2750	7·64	1·515
34	850	·4830	·1610	248	483	2833	7·41	1·471
35	875	·4972	·1657	251	497	2917	7·20	1·429
36	900	·5114	·1704	255	511	3000	7·00	1·389
37	925	·5256	·1752	258	525	3083	6·81	1·352
38	950	·5398	·1799	262	539	3167	6·63	1·316
39	975	·5540	·1846	265	554	3256	6·46	1·282
40	1000	·5682	·1894	269	568	3333	6·30	1·250
41	1025	·5824	·1941	272	582	3417	6·15	1·220
42	1050	·5966	·1989	275	596	3500	6·00	1·191
43	1075	·6108	·2036	279	610	3583	5·86	1·163
44	1100	·6252	·2083	282	624	3667	5·73	1·137
45	1125	·6394	·2131	285	639	3750	5·60	1·111
46	1150	·6536	·2178	289	653	3833	5·48	1·087
47	1175	·6678	·2225	291	667	3917	5·36	1·064
48	1200	·6820	·2273	294	681	4000	5·25	1·042
49	1225	·6962	·2320	297	695	4083	5·14	1·021
50	1250	·7104	·2367	300	710	4167	5·04	1·000

APPENDIX VIII.

TABLE FOR REDUCING THE RESISTANCE OF IRON WIRE MEASURED AT 80° FAHR. TO THE CORRESPONDING RESISTANCE AT ANY TEMPERATURE BETWEEN 55° FAHR. AND 110° FAHR.

Temp. in Degrees F.	100,000	200,000	300,000	400,000	500,000	600,000	700,000	800,000	900,000
55	93889	187778	281667	375556	469445	563334	657223	751112	845001
56	94132	188264	282396	376528	470660	564792	658924	753056	847188
57	94375	188750	283125	377500	471875	566250	660625	755000	849375
58	94618	189236	283854	378472	473090	567708	662326	756944	851562
59	94861	189722	284583	379444	474305	569166	664027	758888	853749
60	95104	190208	283512	380416	475520	570624	665728	760832	855936
61	95347	190694	286041	381388	476735	572082	667429	762776	858123
62	95590	191180	286770	382360	477950	573540	669130	764720	860310
63	95833	191666	287499	383332	479165	574998	670831	766664	860497
64	96076	192152	288228	384304	480380	576456	672532	768608	864684
65	96319	192638	288957	385276	481595	577914	674233	770552	866871
66	96562	193124	289686	386248	482810	579372	675934	772496	869058
67	96805	193610	290415	387220	484025	580830	677635	774440	871245
68	97048	194096	291144	388192	485240	582288	679336	776384	873432
69	97291	194582	291873	389164	486455	583746	681037	778328	875619
70	97534	195068	292602	390136	487670	585204	682738	780272	877806
71	97777	195554	293331	391108	488885	586662	684439	782216	879993
72	98020	196040	294060	392080	490100	588120	686140	784160	882180
73	98263	196526	294789	393052	491315	589578	687831	786104	884367
74	98506	197012	295518	394024	492530	591036	689542	788048	886554
75	98749	197498	296247	394996	493745	592494	691243	789992	888741
76	98992	197984	296976	395968	494960	593952	692944	791936	890928
77	99235	198470	297705	396940	496175	595410	694645	793880	893115
78	99478	198956	298434	397912	497390	596868	696346	795824	895302
79	99721	199442	299163	398884	498605	598326	698047	797768	897489
80	100000	200000	300000	400000	500000	600000	700000	800000	900000
81	100207	200414	300621	400828	501035	601242	701449	801656	901863
82	100450	200900	301350	401800	502250	602700	703150	803600	904050
83	100693	201386	302079	402772	503465	604158	704851	805544	906237
84	100936	201872	302808	403744	504680	605616	706552	807488	908424
85	101179	202358	303537	404716	505895	607074	708253	809432	910611
86	101422	202844	304266	405688	507110	608532	709954	811376	912798
87	101665	203330	304995	406660	508325	609990	711655	813320	914985
88	101908	203816	305724	407632	509540	611448	713356	815264	917172
89	102151	204302	306453	408604	510755	612906	715057	817208	919359
90	102394	204788	307182	409576	511970	614364	716758	819152	921546
91	102637	205274	307911	410548	513185	615822	718459	821096	923733
92	102880	205760	308640	411520	514400	617280	720160	823040	925020
93	103123	206246	309364	412492	515615	618738	721861	824984	928107
94	103366	206732	310098	413464	516830	620196	723562	826928	930294
95	103609	207218	310827	414436	518045	621654	725263	828872	932481
96	103852	207704	311556	415408	519260	623112	726964	830816	934668
97	104095	208190	312285	416380	520475	624570	728665	832760	936855
98	104338	208676	313014	417352	521690	626028	730366	834704	939042
99	104581	209162	313743	418324	522905	627486	732067	836648	941229
100	104824	209648	314472	419296	524120	628944	733768	838592	943116
101	105067	210134	315201	420268	525335	630402	735469	840536	945603
102	105310	210620	315930	421240	526550	631860	737170	842480	947790
103	105553	211106	316659	422212	527765	633318	738871	844424	949977
104	105796	211592	317388	423184	528980	634776	740572	846368	952164
105	106039	212078	318117	424156	530195	636234	742273	848312	954351
106	106282	212564	318846	425128	531410	637692	743974	850256	956538
107	106525	213050	319575	426100	532625	639150	745675	852200	958725
108	106768	213536	320304	427072	533840	640608	747376	854144	960912
109	107011	204022	321033	428044	535055	642066	749077	856088	963099
110	107254	214508	321762	429016	536270	643524	750778	858032	965286

APPENDIX IX.

ON THE DEFLECTION METHOD OF TESTING WITH A REFLECTING GALVANOMETER.

Let D be the deflection produced on a galvanometer of resistance g, shunted with a resistance s, by a steady current C, sent by a constant battery of E. M. F. E, and resistance f, through a known resistance w; and let d be the deflection produced on the same galvanometer, shunted with resistance s', by a steady current C', sent from a constant battery of E. M. F. E', and resistance f', through an unknown resistance x. Then,

$$C = \text{const.} \times F\,(D)$$

$$C' = \text{const.} \times F\,(d)$$

$$\therefore \qquad \frac{C}{C'} = \frac{F\,(D)}{F\,(d)}$$

But

$$C = \frac{E}{f + w + \dfrac{s\,g}{s+g}} \times \frac{s}{s+g}$$

and

$$C' = \frac{E}{f' + x + \dfrac{s'\,g}{s'+g}} \times \frac{s'}{s'+g}$$

Thence

$$\frac{F\,(D)}{F\,(d)} = \frac{E}{E'} \cdot \frac{f' + x + \dfrac{s'\,g}{s'+g}}{f + w + \dfrac{s\,g}{s+g}} \cdot \frac{s}{s'} \cdot \frac{s'+g}{s+g}$$

or putting $\dfrac{s+g}{s} = n$, and $\dfrac{s'+g}{s'} = n'$,

$$\frac{F\,(D)}{F\,(d)} = \frac{E}{E'} \cdot \frac{n'\,(f'+x)+g}{n\,(f+w)+g}$$

and developing x, we have

$$x = \frac{1}{n'}\left[\frac{F\,(D)}{F\,(d)} \cdot \frac{E'}{E}\left\{ n\,(f+w)+g \right\} - g\right] - f'$$

which is the most general formula for finding the magnitude of an unknown resistance by the deflection method of testing; and which can be easily simplified to suit the requirements of special cases.

Another obvious example is when the unknown resistance x to be measured is very great, for then $n' = 1$ $(s' = \infty)$, and $g, f,$ and f' may be neglected, and the expression becomes

$$x = n \frac{F(D)}{F(d)} \cdot \frac{E'}{E} \cdot w$$

If, for instance, $n = 1000, \frac{E'}{E} = 100$, and $w = 10000$ ohms, then

$$x = \frac{F(D)}{F(d)} \cdot 10^3 \text{ megohms.}$$

When a series of observations have to be made with the same instrument, the most convenient form to give the deflection method of testing is that known as the "constant" method, which we now proceed to explain. If a steady current C flowing through any galvanometer produces a permanent deflection of D divisions of the scale, reckoned from the rest position of the index,

$$C = \text{Constant} \times F(D)$$

Whence $\text{Constant} = \frac{C}{F(D)}$

that is, the constant of any galvanometer is the current required to produce the unit deflection. For example, the constant of the Tangent Galvanometer is the current required to produce a deflection of 45° $(\tan 45^\circ = 1)$, while that of the Sine Galvanometer is the current required to produce a deflection of 90° $(\sin 90^\circ = 1)$. In the case of the Thomson's Reflecting Galvanometer, if ϕ is the angle through which the magnet and mirror are turned, then 2ϕ is the angle through which the pencil of light reflected by the mirror is turned; and if r be the distance (measured in scale divisions) of the centre of the magnet from the middle of the scale (supposed to be the zero point), then obviously

$$\tan 2\phi = \frac{D}{r}$$

$$\text{Whence } \phi = \tfrac{1}{2} \tan^{-1} \frac{D}{r}$$

$$= \frac{D}{2r}\left(1 - \frac{D^2}{3r^2}\right) \text{ approximately.}^1$$

$$= \frac{D}{2r} \text{ for small deflections.}$$

---

[1] Developing the right-hand member of the equation in series by Maclaurin's Theorem, and neglecting terms after the second in the result.

Hence, when the deflection is small compared with the distance of the scale from the mirror, the angle through which the needle is deviated is directly proportional to the scale reading. According to the practice in this department, the scale is 2 feet long (1 foot lying on each side of the centre zero line), is graduated to $\frac{1}{50}$ inch, and is set up at about 3 feet from the mirror, so that

$$\text{for a deflection of 180 divisions,} \ \frac{D^2}{3r^2} = 0{\cdot}01, \text{ and}$$

$$\text{,, \quad 360 \quad ,, \quad ,,} \quad = 0{\cdot}04 \text{ only.}$$

Hence for practical purposes we may always consider the angle to be directly proportional to the scale reading, and we can keep this true within 1 % by avoiding readings greater than 180 divisions.[1]

The current C producing the deflection D is, for all angles that we have to deal with, proportional to the angle through which the magnet is deviated, and, since the latter is proportional to the scale reading, the current C is proportional to the scale reading.

Hence

$$\text{Constant} \qquad = \frac{C}{D}$$

The constant of the Reflecting Galvanometer is the current required to produce a deflection of one scale division.

$$\text{Now} \qquad C = \frac{E}{W}$$

where E is the E. M. F. employed in taking the constant, and W is the total resistance in circuit,

$$\text{Whence Constant} \qquad = \frac{E}{DW}$$

It is not always convenient to employ a resistance W sufficiently great to attain the requisite degree of sensibility, and it is therefore usual to shunt the galvanometer by a known and constant small resistance, bearing a convenient ratio to the galvanometer resistance, when taking the constant of the instrument. If, for instance, we desired the constant to be 0·001 microweber; and E were $= 1$ volt (approximately the E. M. F. of a Minotto element), and $D = 100$ divisions of the scale, then the resistance W would have to be made 10 megohms.

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[1] If we are obliged to take greater readings than this, the best way is to adjust the zero point of the index at 150 divisions to the one side of the middle of the scale, which will give us a range of 300 divisions, by reading up to 150 divisions on the opposite side of the middle of the scale. When our zero point is so adjusted, we must always reverse the galvanometer poles at the same time as we reverse the battery poles.

Each galvanometer, however, is provided with a shunt box containing three coils, whose resistances are respectively equal to $\frac{1}{9}$, $\frac{1}{99}$, and $\frac{1}{999}$ of the resistance of the galvanometer. According as we join either of these shunts between the terminals of the galvanometer, then $\frac{9}{10}$, $\frac{99}{100}$, or $\frac{999}{1000}$ of the current will be shunted, and only $\frac{1}{10}$, $\frac{1}{100}$, or $\frac{1}{1000}$ part of it will pass through the galvanometer.

If, then, we employ the $\frac{1}{1000}$ shunt when taking the constant, we shall have

$$\text{Constant} = \frac{C}{D}$$

$$\therefore \qquad \text{Constant}^{1} = \frac{E}{1000\ D\ w} = K \text{ say.}$$

So that if we take $E = 1$ volt, and $D = 100$ divisions of the scale, in order to have the constant $= 0{\cdot}001$ microweber, we require to make $w = 10000$ ohms only.

If we do not require such a delicate adjustment, we may employ the $\frac{1}{100}$, or even the $\frac{1}{10}$ shunt in taking the constant, when C will become $0{\cdot}01$ or $0{\cdot}1$ microweber.

Having adjusted the constant, if an E. M. F. E' volts produces a current of C' microwebers, and gives a deflection of d divisions of the scale, through an unknown resistance x megohms,

$$C' = K\ d$$

$$\frac{E'}{x}{}^{2} = K\ d$$

$$\text{Whence} \qquad x = \frac{E'}{K\ d}$$

Say, for instance, $E' = 100$ volts, and $K = 0{\cdot}001$ microweber, then,

$$x = \frac{10^5}{d} \text{ megohms.}$$

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[1] Let f = the resistance of the battery, g = resistance of the galvanometer, w = the added resistance, and n = the multiplying power of the shunt (*i.e.*, $n = \frac{s+g}{s}$, where s is the resistance of the shunt), then

$$C = \frac{E}{f + w + \frac{g}{n}} \times \frac{1}{n}$$

$$= \frac{E}{n\ (f+w) + g}$$

but g may be neglected against $n\ (f+w)$, and f against w,

$$\therefore \qquad C = \frac{E}{n\ w}$$

[2] x includes the relatively small resistance of the galvanometer and battery, which may be neglected when measuring great resistances.

It may sometimes be required to measure a small resistance by the deflection method, when no Bridge or Differential Galvanometer is at hand. In such a case, the zero should be set at 150 divisions to the one side of the middle of the scale, and the galvanometer should be shunted by means of a short copper wire connected between its terminals, so as to give a deflection of 300 divisions (*i.e.*, to about 150 divisions on the opposite side of the middle of the scale), with a single Minotto cell through *no added* resistance.

The general expression for x is

$$x = \frac{1}{n'}\left[\frac{D}{d}\cdot\frac{E'}{E}\cdot\left\{n\,(f+w)+g\right\}-g\right]-f'$$

and if we take $n' = n$, and $E' - E$, then $f' = f$, and

$$x = \frac{D}{d}\left(f+w+\frac{g}{n}\right)-\frac{g}{n}-f$$

If w is adjusted so that $D = d$, then

$$x = w$$

If we cannot exactly reproduce the deflection d, say w' when inserted gives a deflection $d+\delta'$, and w'' when inserted gives a deflection $d+\delta''$, then

$$x = w' + (w''-w')\,\frac{\delta'}{\delta'+\delta''}$$

But if D not $= d$, then

$$x = \frac{D}{d}\,(f+w)-f.$$

as on account of the smallness of $\frac{g}{n}$ it may be neglected even against f, the internal resistance of a single cell.

And, finally, if $w = 0$,

$$x = \left(\frac{D}{d}-1\right)f$$

PRACTICAL REMARKS.—The galvanometer should always be first set up *without* the permanent directive magnet. When the fibre has been raised by turning the milled-headed screw, and the instrument has been levelled with reference to the spirit-level attached to its base for the purpose, so that the suspension swings free, it will be found that the pair of needles, not being perfectly astatic, will set in the magnetic meridian under the influence of the earth's magnetism alone. The galvanometer should then be turned (its level being always carefully maintained) until the plane of the coils is parallel to the magnetic meridian.

The scale and lamp should then be set up so that the reflected pencil of light strikes the zero point of the scale. The scale should be carefully levelled and turned so that it is parallel to the galvanometer coils. The parallelism of the scale and galvanometer may be ascertained by making a series of measurements with a tape from the middle and two ends of the scale to the different points of the instrument. The lens should be adjusted so as to give a clearly defined image of the wire crossing the slit in front of the lamp. The permanent magnet may then be fixed in its place and adjusted at pleasure, so as to increase or diminish the directive influence of the earth's magnetism on the needles. When a Reflecting Galvanometer is to be permanently employed at one place for testing (*e.g.*, as at a store depôt for insulator testing), it is desirable to erect a masonry pedestal on which to place it. The galvanometer alone should stand on the pedestal: the other apparatus should be placed on a steady table brought close to, but not touching, the pedestal. The terminals of the shunt box should be connected with those of the galvanometer by light silk-covered copper wire. With these arrangements, the operations performed on the table will not interfere with the equilibrium of the galvanometer. The tester should remove all magnetic substances. such as pen-knives and keys, from his pockets. When about to test an unknown resistance with a Thomson's galvanometer, short circuit the galvanometer and insert the 10^{-3} shunt. First apply the current, and then remove the short-circuiting stopper. If the 10^{-3} does not allow a sufficiently large deflection, then try the 10^{-2} shunt, and so on.

APPENDIX X.

CABLE TESTING.

General Remarks.—The great rivers that have to be crossed in India present difficulties that are unknown to the Telegraph Engineer in Europe; and this not only on account of their dimensions, but also on account of their character. If a river bed were tolerably constant in form and position, if the water always flowed approximately at the same level, and if the banks were sound and stable, then a strong gutta-percha cable, with its shore ends well buried to protect them from the action of the atmosphere, would answer all requirements. But in many of the Indian rivers the difference of level is 20, 30, and even 60 feet between the dry season and the floods, when the land on both sides of the rivers is often under water for miles; banks are cut away or extended, islands are built up or demolished, and new channels are scoured out and old ones deserted. The junction-points between the cables and the land lines have, therefore, to be thrown far back from the rivers in order to protect them from being washed away, and the different parts of the cable are consequently liable to be under water at one season of the year and on dry land at another. It is impossible to regulate the position even of the cable: sometimes and in some places it will be found lying on the surface, while at others it will be buried fathoms deep in the river bed. There is no remedy for this, and the only mitigation of the evil is close inspection early in the dry season, and re-burying all exposed parts. In a tropical climate, this exposure, and this alteration of wet and dryness, must always remain most prejudicial to cables. Every effort, therefore, has been made of recent years to eliminate cables as much as possible. But although advantage has been taken of railway bridges, and special masts have in several instances been erected to carry aërial wires, yet many rivers still remain that must be cabled. Formerly cables insulated with gutta-percha were largely employed in India, but this substance was not so well prepared then, and its nature and properties were not so well understood as now, and it was not considered suitable (as it undoubtedly is not in some respects), and was temporarily abandoned. Sir W. O'Shaughnessy analysed some altered gutta-percha in 1856,[1] and found that the gum had been rendered resinous by oxidation. His results were subsequently confirmed by the researches of Hoffman and Miller. Heat, light, and exposure to the air favour this change. At a comparatively low temperature (not much above 100° Fahr.) gutta-percha softens, and therefore if a gutta-percha cable is bent when exposed to heat, the copper conductor is liable to force its way through the dielectric, become eccentric, and possibly cause a fault. Gutta-percha cable, therefore, should never be exposed to the direct rays of the sun.

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[1] See Sir W. O'Shaughnessy's "Instructions for the Construction of Subterranean Lines," 1859.

Hooper's India-rubber cable core was subsequently introduced into India. In the case of Hooper's cable core the conductor is covered with three distinct layers of differently prepared India-rubber; namely, first a layer of pure India-rubber (next the conductor), then a layer of India-rubber saturated with zinc oxide, and finally a layer of vulcanised India-rubber outside. The object of using the zinc oxide is to prevent the sulphur of the vulcanised India-rubber reaching and corroding the copper conductor. This material possesses one quality which renders it eminently suitable for India, namely, that it is not affected by heat at ordinary temperatures. It bears a great deal of handling and rough usage, and keeps mechanically good for a long time in air: it stands, therefore, unrivalled for indoor work, such as office and battery connections, leading wires, &c., and is exclusively employed for these purposes in India. Hooper's cable core, however, although when new possessing a specific insulation greater than gutta-percha (some core has been landed in India with an insulation of 8000 megohms per mile), has been found to rapidly decline in insulation, and to ultimately lose its insulating power altogether (several cables, after being three or four years in use, have been found to have an insulation of only 300 ohms per mile). This does not arise, as has been abundantly proved, from any specific "faults," but from a general deterioration of the dielectric. Hence, for the purpose of cable manufacture, Hooper's material has been abandoned, and recourse has been again had to gutta-percha.

CONDITIONS TO BE FULFILLED BY A RIVER CABLE.—In the case of ocean cable, the conditions to be fulfilled are, from a mechanical point of view, to have the maximum strength with the minimum weight; and, from an electrical point of view, to obtain good insulation, combined with low inductive capacity and high conductivity. The first condition is evidently necessary, in order to allow of the cable being raised from the great depths of the ocean (sometimes 3000 fathoms) for repair, in case of the occurrence of a fault, while the second is necessary to insure efficient communication at a commercially remunerative speed. The case of river cables is quite different. They never have to be raised from such depths, and consequently never have to support such great lengths of themselves, and may therefore be made far heavier in proportion to their strength than ocean cables. Again, river cables are so short (rarely in this country exceeding two miles in length), that their retardative influence is insensible, and therefore high conductivity and low inductive capacity are not vital desiderata, as in the case of ocean cables. The two points, therefore, that demand special attention in the case of river cables, are good insulation and great absolute strength. The latter of these conditions is easily fulfilled by protecting the cables with massive iron guards (in India 12 iron wires, each weighing 900 lbs. per mile, are employed). The conductor usually consists of a strand of 7 copper wires (six laid round one) of from No. 16 to No. 22 B. W. G. The strand is imbedded for solidity in Chatterton's compound.

The gutta-percha is put on in four layers, connected by thin layers of Chatterton's compound, and has a total thickness of from 0·08 to 0·16 inch. The deterioration of gutta-percha when exposed to the atmosphere (when permanently under water it scarcely alters at all)[1] has been shown to arise from a gradual process of oxidation. The decline in insulation of gutta-percha covered wire is, therefore, slow and progressive, unlike that in the case of Hooper's material, which is vast and sudden. In the case of a gutta-percha cable, this oxidation naturally goes on from the outside of the core inwards; and, therefore, clearly a gutta-percha cable will last proportionately longer, *cæteris paribus*, as we increase the thickness of the dielectric. In the case of ocean cables, the mechanical conditions to be fulfilled put a limit to this thickness; but with river cables no such conditions exist, and therefore the dielectric may be very well made ¼ inch thick. In America this fact appears to have been recognised and acted upon.[2]

CABLE TESTING.—Cables under manufacture have to be constantly tested during the process of covering the conductor with insulating material, in order to see that no flaw occurs. We do not in India, however, undertake the covering of the conductor with gutta-percha, but import the completed "cable core" from England, and only put on the iron guards out here. The core has to be tested immediately on its receipt from England, to ascertain whether it is in good order. In the first instance, it should be tested on the drum and in the tank just as it is received. Then the drum should be taken out of the tank and placed under water in one of the permanent tanks, and the core tested again immediately. The core should be daily tested after this until it is found to have recovered from the effects of the voyage, and assumed its normal condition. Finally, the "electrification" test should be made, and, if this prove satisfactory, the core may be passed as perfect. Subsequently the cable must be tested periodically, to know that it maintains its normal condition, until such time as it may be taken out of the tank to be made up into cable. During the process of manufacture the core must be tested before and after each operation is performed, to see that it has received no injury, *e.g.*, it must be tested before being removed from the cable tank, and after being placed in the cable house; before being covered with the first serving of hemp, and after being covered with the first serving of hemp, and so on. Further, during the manufacture of a cable, it should be tested daily at the hour when the machinery is stopped for the workmen to have their dinner. When the cable is completed and coiled into the tank, its electrification curve must be taken again. When the cable is to be issued from store, it must be tested before being removed from the tank, and again when coiled into the lighter. After the latter test of the cable, its ends must be sealed up.

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[1] A portion of the unprotected gutta-percha covered wire that was laid across the Channel in August 1850, has been recently recovered and examined. After immersion for twenty-five years in the sea, the gutta-percha was found to be in perfect condition, both mechanically and electrically.

[2] See Louis Figuier's "Merveilles de la Science," where a full-size section of an American river cable is given.

On arrival at its destination the cable should be again tested before being laid; and after being laid it should be tested, and its electrification curve taken. Finally, all cables must be tested periodically after being laid, to ascertain whether they are maintaining their normal condition.

Execution of Cable Tests—*Capacity.*—This is measured by comparing the capacity of the cable with that of a standard condenser of known and constant capacity. The methods of comparing capacities have been already treated of in this section. (Pars. III. to IX.)

The absolute capacity of a cable is expressed as follows:—

$$S = 2{\cdot}7 \frac{\sigma\, l}{log_{10} \frac{D}{d}} \text{ microfarads}$$

where d = diameter of conductor, and D = diameter of core, both measured in terms of any the same unit of length; l = length of cable; and σ = the capacity in microfarads between opposite faces of a cube of unit length and unit sectional area. Thus if l is measured in yards, σ is the capacity in microfarads of a yard cube; if l is in knots, σ is the capacity in microfarads of a knot cube. The value of the capacity S will manifestly vary, therefore, with the dimensions of the cable. But by the help of the above formula, having measured S, we can calculate σ, which is entirely independent of the dimensions of the particular cable under test, and will afford a measure of the "specific inductive capacity" of the material employed in insulating the cable.

Thus,

$$\sigma = 0{\cdot}3665 \frac{S}{l}\, log_{10} \frac{D}{d} \text{ microfarads}$$

The value of σ is about 0·0687 *mf.* per knot cube for gutta-percha; and about 0·0543 *mf.* per knot cube for Hooper's material.

Conduction.—The resistance of the conductor is usually measured with a Wheatstone's Bridge; but a method for measuring the conductor resistance of even a very short cable by means of a Thomson's Reflecting Galvanometer has been given in Appendix IX. Corrections for temperature should invariably be introduced in order to render the results of the different tests comparable. The standard temperature adopted for cables is 75° Fahr., and therefore all copper resistances should be reduced to this temperature for comparison. The formula to be employed is: —

$$R_{t'} = \frac{1 + (t' - 32)\ 0{\cdot}00215}{1 + (t - 32)\ 0{\cdot}00215} R_t$$

When a cable is under water, the temperature of the water should always be ascertained. The absolute resistance of the conductor of any cable is expressed as follows :—

$$R = \varkappa \frac{l}{a} \text{ ohms}$$

where l = length of the conductor, and a = its sectional area, expressed in terms of any the same unit of length ; and $\varkappa$ = the resistance in ohms between opposite faces of a cube of unit length and unit sectional area.

From this formula we deduce

$$\varkappa = \frac{a}{l} R \text{ ohms}$$

from which we can calculate $\varkappa$, if we know a and l and measure R. The resistance between opposite faces of a knot cube of pure copper is $= 885 \times 10^{-14}$ ohms at 32° Fahr. By comparing the resistance between opposite faces of a cube of the same dimensions of the conductor with this resistance corrected for temperature, we can ascertain the percentage conductivity of the copper employed in manufacturing the conductor.

Insulation.—The insulation of cables is always measured in this department either with a Bridge, or with a Thomson's Reflecting Galvanometer by the "constant" method described in Appendix IX. A battery of 100 Minotto cells is employed. Another method of testing the insulation of a cable is by charging the conductor to a given potential, leaving it insulated for a certain time, and then measuring its potential; or by charging the cable, and first discharging it immediately through a galvanometer and noting the deflection, and then charging it, allowing it to remain insulated for a certain time, and then discharging it through the galvanometer. By the ratio of the potentials in the first case, or of the discharges in the second, the insulation is measured. This method is not employed in India, but a very practical way of testing the insulation of a river cable from time to time is suggested by it, namely, to charge the cable with a battery sufficiently strong for the immediate discharge of the cable to be felt, if not by the fingers, at least by the tongue, then charge the cable again and see how long it may be left insulated and yet the discharge be felt in the same way. When measuring the insulation of cables, the temperature by the wet and dry bulb thermometers should invariably be noted; and, if the cables are in water, the temperature of the water should be taken.

According to Clark and Sabine

$$\log w'' = \log w' - (t'' - t') \log 0{\cdot}9399$$

where

$w' =$ the resistance of gutta-percha at t'° F.

and $w'' =$,, ,, at t''° F.

The standard temperature of reference is 75° Fahr.

The expression for the insulation resistance of any cable is as follows:—

$$I = 0{\cdot}3665 \frac{\varrho}{l} \log_{10} \frac{D}{d} \text{ megohms}$$

where $d =$ diameter of conductor, and $D =$ diameter of core (d and D must be referred to any the same unit of length); $l =$ length of the cable; and ϱ is the resistance in megohms between opposite faces of a cube of unit length and unit sectional area. From this we deduce

$$\varrho = 2{\cdot}7 \frac{l\,I}{\log_{10} \frac{D}{d}} \text{ megohms.}$$

If l is expressed in yards, then ϱ will be the resistance in megohms of a yard cube; and if l is expressed in knots, ϱ will be the resistance in megohms of a knot cube. $\varrho = 2100$ megohms per knot cube at 75° Fahr. for gutta-percha, and $\varrho = 40950$ megohms for Hooper's material. The value obtained for ϱ affords a measure of the "specific resistance" of the insulating material employed.

Preparation of Ends of Cable.—Before commencing the tests of any cable, its ends must be prepared as follows. The end of the conductor must be thoroughly cleaned so as to afford good contact; and the insulating material must be tapered down so as to present a fresh and clean surface. The end of the insulating material must be warmed over a spirit lamp, to drive off moisture, and then dipped for a minute or so in hot melted solid paraffin, which on cooling will form a highly insulating film preventing surface leakage.

Electrification.—Owing to the phenomenon of "electrification" the insulation of a cable appears to increase with the time the testing current (whether positive or negative) is kept on, hence the apparent insulation of a cable at any moment is a function of the time the testing current has been applied. In order to render tests comparable *inter se*, therefore, the testing current must be applied for a uniform time before the readings are taken. The time generally adopted in practice is one minute; and when in reports no reference is made to time, it is always implied that the readings were taken after one minute's electrification. It is preferable, however, to invariably state the time. The cable must be thoroughly discharged, by being connected directly to earth, before commencing each test. The "electrification curve" of a cable is found by applying the testing current permanently and noting the readings at fixed intervals of time. The cable is first discharged by the conductor being put directly to earth, and then a positive testing current from 100 Minotto cells is applied for 30 minutes, readings being constantly taken and the times noted. Then the cable is again thoroughly discharged, the battery is reversed, and a negative testing current is applied for 30 minutes, readings being again taken as before.

Reckoning time along the abscissa axis, and taking the ordinates to represent the insulation resistances, we obtain a series of points representing the insulation at each instant. Drawing a line through these points, we have a curve exhibiting the rate of electrification of the cable. The criteria of the goodness of a cable are that the apparent rate of increase of insulation should be steady and continuous, as well with a positive as with a negative test current, and that the electrification curves derived from positive and negative tests should be parallel.

Note.—When testing cables through leading wires (*i.e.*, when the ends of the cable cannot be brought to the testing board), the insulation of the leading wires should be perfect, and their capacity and conductor resistance should be carefully ascertained and allowed for in the results.

PROTECTION OF RIVER CABLES FROM LIGHTNING.—Intercalated as they necessarily are in the circuit of overland lines, river cables naturally incur great risk of injury from lightning, which having struck the wire (as it not infrequently does) in the neighbourhood of the cable, may, in preference to breaking the insulators, and thus clearing a path to earth, pass along the wire to the cable, and then burst its way through the insulating material from the conductor to the guards. In addition to the plate and vacuum lightning dischargers employed, a practical protection is afforded by the spare bights of cable always left in the inshore trenches,[1] for the disruptive discharge will most probably take place in the shore end, close to the junction house, where the fault may be discovered and cut out. The terminal posts, outside the cable houses, should invariably be provided with safety lightning protectors.

REPAIRS TO RIVER CABLES.—Before abandoning a river cable that has become defective, it should be invariably cut at the river banks and tested, as it will be frequently found that the shore ends alone are faulty; and, indeed, that even they are only defective in certain parts, which have been injured mechanically, or through exposure from being imperfectly buried, or by a discharge of lightning. In such a case the cable can be readily repaired, either by cutting out the defective parts, or by fitting new shore ends. But when the fault is found to exist in the river itself, it is a matter of great difficulty. It is rarely possible to lift the whole of a river cable, as some portion of it, of greater or lesser extent, is almost always buried to such a depth in the river bed that it cannot be extricated. If a cable that has been suffering from defective insulation commences to also exhibit partial discontinuity, immediate steps should be taken to repair or replace it, as it may cease to work at any moment.

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[1] See Sir W. O'Shaughnessy's "Instructions for the Preparation of River Cables," p. 5, 1858.

ON THE FITTING OF CABLE HOUSES.—The following instructions are intended for the guidance of all officers who may be charged with the fitting up or the inspection of cable houses—it being premised that, in point of material and execution, the arrangements in cable houses must be on a par with those in signal offices. The wires leading in from the terminal post must consist of insulated wires—by preference of Hooper's thick cable core—and they must be carried, without break or flaw of insulation, from the post to the upper plate of the lightning protector. Particular attention must obviously be given to those portions of the wire that are in contact with uninsulated bodies, such as the sides of the house, the table on which the lightning protector stands, &c. One end of the leading-in wire is to be carefully *soldered* to the line wire. The ends of the cables must not be cut short so as to just reach the lightning protector in its actual position, but must be left of such a length[1] (at least two or three yards) as to admit of a possible ulterior change in the position of the lightning protector, and of the end of the cable being at any time conveniently brought on the table for testing purposes. The slack must not be coiled into a spiral, which cracks the insulating material, but must be tied up under the table in a coil of at least two feet in diameter. For a length of at least two feet above the surface of ground the iron guards must be left on the cable, the ends of the guards being served with binding wire; and from this point up to about one foot from the end, the hemp or jute bedding must be left on the core, the ends of the bedding being served with twine. About two inches of the insulating material should be removed from the end of the core, and the conductor carefully cleaned (if stranded, each wire to be cleaned separately). In re-twisting a stranded conductor, care must be taken not to over-twist the spiral, which renders the strands very apt to break. In order to obviate the necessity of cutting the ends of the insulating material every time the cables are tested, and generally to prevent surface leakage at the ends of the cables, they must be fitted with ebonite pencils (procurable on indent from the store branch). First the ends of the insulating material are to be carefully tapered down for about three inches—if of gutta-percha, by paring with a knife; if of India rubber, by cutting with a pair of scissors—warmed over a spirit lamp to drive off moisture, and then dipped into melted paraffin; next the ends of the cables are to be passed into the pencils; and then melted paraffin is to be poured into the pencil around the core. Permanent good insulation at these points will be insured by the cable guard's dusting the pencils at the same time as he cleans the lightning protectors. Whenever it should be found necessary (this, however, must be very exceptional) to make a joint anywhere in the insulated wire in the cable houses, the joint must be made strictly in accordance with the instructions laid down in chapter 7, sections B and C, of the Construction Pamphlet. Every cable house must be provided with a cheap but strong table, at least 2′ × 2′, on which the lightning protector is to stand, and which will serve to place the instruments on when the cable is tested.

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[1] This will do away also with all chance of any strain being thrown on to the conductor of the cable.

When the cable houses are raised from the ground on piles, a permanent flight of wooden steps up to the door must be erected; and ladders, which are both liable to break and to be stolen, are not to be used. When two or more cables terminate in a cable house, each of the cables must be given a number distinct from that of the line on which it works, by which it shall be recognised, and a zinc label, stamped with its number, is to be fastened by a piece of binding wire to each cable. This will prevent all confusion in the records of the cables, in the event of their being subsequently interchanged for any reason among the lines. When a number of cables on important lines cross the same river at the same point, as they will require to be frequently tested, it will be advisable to have a testing battery of 20 Minotto elements, ready placed on an insulated[1] stand in one of the cable houses. These elements should be prepared, brought into working order, and then allowed to stand—circuit open—with water in them, but *without* zincs. The cable guard should be made responsible for water being kept in the jars.

In one of the cable houses of every river crossed by cables, a visiting book should be placed (in charge of the cable guard), in which the following information concerning each cable must be given:—

i. No. of cable,
ii. Length of cable between cable houses,
iii. Length of surplus cable on each bank,
iv. Date of laying cable,

all tests made of the cables from time to time must be recorded, and inspecting officers must enter the dates of their visits, together with all such remarks as the state of the cable houses, &c., appear to call for.

Recording Cable Tests.—See the form attached, which will be clear without explanation.

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[1] Best done by placing the stand on ordinary battery jars inverted.

REGISTER OF CORE AND TABLE TESTS.

DATE.			TEMPERATURE.		Name, description, and dimensions of the Core or Cable.	Length.	INSULATION IN MEGOHMS.			CONDUCTION IN OHMS.			CAPACITY IN MICRO-FARADS.			REMARKS.
Month.	Day.	Hour.	$\frac{\text{Wet}}{\text{Dry}}$.	Of the Core or Cable.			Absolute.	Per Knot.	Per Knot Cube.	Absolute.	Per Knot.	Per Knot Cube.	Absolute.	Per Knot.	Per Knot Cube.	

APPENDIX XI.

INSTRUCTIONS FOR TESTING INSULATORS.

1. The following method of quantitatively testing Insulators is adopted.

2. The standard of resistance for any insulator should not be less than 2000 megohms.

2000 megohms as the minimum standard for insulators is practically quite high enough even for the longest main line in India, and it is also sufficiently low to facilitate the testing. Besides this it seems to be a fact that, if the material of an insulator is conducting for some reason or other, the resistance offered is generally much lower than 2000 megohms, even lower than 10 megohms. The above minimum standard, therefore, is a sufficient safe-guard against passing defective porcelains.

3. For testing Insulators a sensitive Thomson's Reflecting Galvanometer is necessary, and an electromotive force of not less than that of 100 Minotto's cells. The constant of the Reflecting Galvanometer must be regulated in such a way as to give a deflection of about 100 divisions of the scale with 1 cell through 10 megohms. (See Appendix IX.) The constant of the galvanometer is to taken regularly three times a day—*i.e.*, before testing begins, at about noon, and when testing is over; and for calculating the resistances, the average of the three constants is to be used.

4. All tests are to be recorded. (See Form annexed.)

5. One hundred finished insulators at a time should be placed inverted in a box lined with zinc—the latter to be connected permanently with one pole of the testing battery. To secure a perfect contact between the zinc lining and the outside of each insulator the box must contain water to a depth of not more than two inches. (This will be just high enough to reach the exposed cement of the perforated hood insulator.) Water is also to be poured into the porcelain cups themselves in sufficient quantity to reach within an inch of the rims. Several such boxes, each containing 100 insulators, may be prepared at a time.

6. A dry and wet bulb thermometer should also be hung up, and the readings noted whenever insulators are being tested, since days on which the relative humidity is great are unsuited for testing on account of the rapid deposition of dew on the rims of the Insulators. Before

testing begins the rims of the insulators are to be carefully wiped clean and dry. If, during damp weather, this should prove insufficient, the rims must be dried by holding a hot iron over them.

7. One pole of the battery being joined to the zinc lining of the boxes, the other pole is to be joined to one terminal of the galvanometer, and to the other terminal of the galvanometer is to be attached one end of an insulated wire, which, if its other end be insulated, will give *no* deflection with 100 cells when *no* shunt is used. The insulation of this leading wire should be tested in this way thrice a day at the same time that the constant of the galvanometer is taken.

8. The insulation of the leading wire being taken, touch with the free end of this wire the stalks, one by one, of the insulators, and notice the deflection which 100 cells give at the galvanometer shunted with the $\frac{1}{999}$th shunt. Reject all insulators that give any deflection. Repeat the above with the galvanometer unshunted; then the magnitude of the deflection caused by each insulator will give the tester at once an idea, without any calculation, whether the insulator under test is above or below the standard (2000 megohms). If, for instance, the galvanometer gives with 1 cell through 10 megohms a deflection of 100 divisions of the scale, then by using 100 cells through the unknown resistance of one insulator the deflection must be not more than 50 divisions of the scale. (See Appendix IX.) Thus all insulators giving less than about 50 divisions of the scale have a resistance of more than 2000 megohms and can be passed, while those that give more than 50 divisions of the scale have less than about 2000 megohms, and are to be rejected and removed from the box.

9. The good insulators remaining in the boxes have then to undergo the final test. For this purpose all the stalks are to be first connected by means of a *bare* copper wire, to which the insulated leading wire is attached, and the deflection at the galvanometer observed both with the positive and negative current—in each case after the current has been on for one minute. From these readings in the usual way the absolute resistance of the whole number can be calculated (see Appendix IX.), and from this the average resistance per insulator.

10. Those that are rejected out of each box are to be investigated further with a view to discover the cause of the low resistance, which may lead, possibly, to improvement in the manufacture.

11. Before being tested, the insulators should have been soaked for at least 24 hours in water.

12. Both the leading wires must consist of perfectly insulated wire, best of Hooper's thick cable core.

13. Before the final test with reverse currents is taken, the insulators must be thoroughly discharged, to make the positive and negative tests comparable, (Good insulators become electrified by the testing current for the same reason as a good cable.)

14. When finished insulators, that have been tested and passed by the India Office Inspector of Telegraph Stores, are received from England, only 5% of the total number received should in the first

instance be tested. If this number be found good, then the remainder need not be tested. But should any of the number prove defective, the whole of the insulators must be tested.

15. When cups for insulators, that have not been tested in Europe, are received, only 10% of the total number received should in the first instance be tested. If this number be found good, then the cups may be at once made up into insulators. But should any of the number prove defective, the whole of the cups must be tested before being made up into insulators. When fitting stalks into cups, a wad of *numda* (country-made felt) should always be dropped into the insulator before putting in the stalk, to prevent direct contact between the iron stalk and the cup.

16. All finished insulators that have been made up locally must invariably be tested in accordance with the above rules before being passed into stock.

REGISTER OF INSULATOR TESTS.

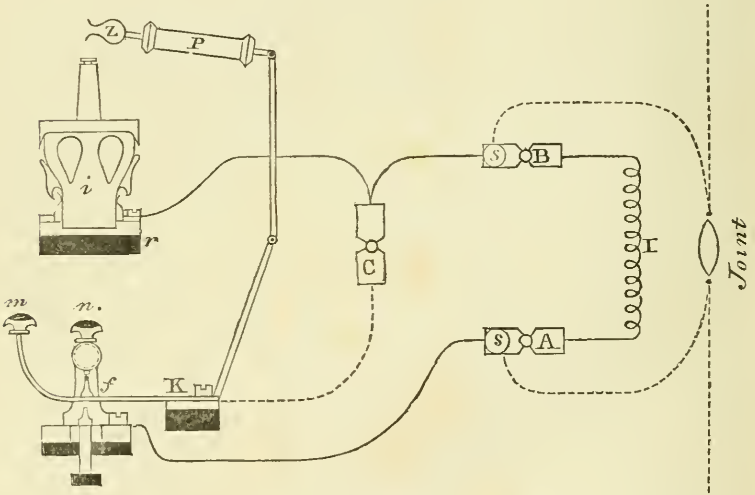
No. of Test.	TIME.		CONSTANT OF INSTRUMENT.	Thermometer $\frac{\text{wet}}{\text{dry}}$ bulb.	INSULATORS PASSED.								Rejected.	REMARKS.
	Date.	Hours.	Microwebers.		Pattern.	Porcelain.	No. of Insulators.	*E.*	Deflection +	−	Resistance in megohms.			
											Absolute.	Per Insulator.		

APPENDIX XII.

APPARATUS FOR DETECTING DEFECTIVE JOINTS AND INSULATORS.

The following is a simple and practical method of detecting electrically defective insulators in Telegraph Lines.

The principle of the method is to send a magneto-electric current through the resistance of the insulator, and to measure the strength of the current by its effect on the tester's sense of feeling or taste.



From the accompanying diagram the connections of the apparatus will be readily understood. *I* is the coil of a magneto-electric machine, the terminals of which, *A* and *B*, are carefully insulated with ebonite from each other and from the ground. Terminal *B* is in permanent contact with the "insulator receiver" *r*. This "receiver" *r* consists of four steel springs in metallic contact with a brass plate insulated on ebonite. Each of the springs is tipped with platinum on its inner face, to insure good contact with the iron hood of the insulator under test.[1] Terminal *A* is in permanent contact with the fixed knob *n* forming part of the key *K*. This knob *n* is immovable, and is tipped with platinum on the top.

In metallic contact with the body of the key *K* is a brass rod hinged in three places, so as to be movable in any direction. The uppermost piece of the rod is insulated by an ebonite tube *p*, and terminates in a double spring of steel *z*, faced with platinum, to make a good contact with the stalk of the insulator. The rod *p* we shall designate the "insulator pencil." A strong steel spring is attached to the key *K*, bent upwards and terminating in a brass knob *m*, tipped with platinum. This spring in its normal position, *i.e.*, when not pressed down, completes the circuit by making metallic contact at *f*.

C is a clamp interposed between *A* and *B*, which when plugged up connects the terminal *A* permanently with *B*, and is only used when testing joints. The whole instrument is constructed lightly, but at the same time strongly, and can easily be carried by one cooly along the Line. The various portions of the instrument which require to be insulated are mounted on ebonite.

§ 1. *To test the efficiency of the instrument.*

Before the tester proceeds with testing, he must satisfy himself that his instrument is in perfect order. This is to be done as follows:—

Put in the plugs *A* and *B*, but leave out the plug *C*. Let the insulator pencil *p* make metallic contact with the receiver *r*, put one finger of the left hand on knob *n*, a finger of the same hand on knob *m*, but without pressing the latter knob down, *i.e.*, without opening the contact at *f*, and give the handle of the machine a sharp turn with the right hand. Then nothing should be felt by the finger, because the current produced, however strong, is short-circuited at *f*. As soon, however, as the tester presses down the knob *m*, *i.e.*, opens the contact *f*, all the current produced passes through him from one knob to the other giving him strong shocks, because there is no external resistance in the circuit except that offered by the tester's body. If the instrument is in perfect order, it should give in this way very strong shocks even when turning very slowly. By this it is proved that the instrument generates a current sufficiently strong to detect any insulators really defective, *i.e.*, under a certain maximum resistance. Now repeat the same experiment by putting the insulator pencil *p* in the air; *i.e.*, making the external resistance infinite: then no shocks should be felt by the fingers, even when turning most rapidly; also, not the slightest sour taste should be detected if the tongue of the tester be substituted for the finger at the knob *n* and if turning rapidly for a moment. By this test it is proved that no leakage exists between p and r, and that, therefore, no perfect insulators (which have an insulation over a certain determined limit) can be rejected by the tester. Further, with each instrument are issued a number of defective insulators, and one perfect one, each having its resistance marked; with these insulators the tester should practise, to gain the necessary experience, and they should also be taken out on the Line (as standards) to test the detector when required.

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[1] Should the insulator have no iron hood, as in the case of the Prussian pattern, then it must be placed inverted in a small metal vessel containing mercury or water.

§ 2. *Testing Insulators.*

The tester will proceed as follows :—

Wash the insulator to be tested thoroughly, put it inverted in the receiver r, and connect the insulator pencil p with the stalk. Then turn with the right hand the handle of the machine, having two fingers of the left on the knobs m and n, as before described, but without pressing down the knob m, *i.e.*, without opening contact at f. Thus, however bad the insulator under test may be, and however quickly the tester may turn the handle, he will feel nothing whatever; but as soon as he presses down the knob m, the metallic circuit at f is opened, and the alternating positive and negative magneto-electric currents have to pass from one finger to the other, and consequently, if strong enough, will give the tester sensible shocks, by which he is at once informed that the insulator under test is defective, and much under the fixed standard of insulation. If, however, the tester should not feel any current through his fingers (a comparatively rough galvanoscope), he has only to repeat the experiment by placing his tongue on the knob[1] n while the one finger of the left hand still presses down the knob m. If even now no current is felt by the tester through this most delicate galvanoscope, the tongue, he can rest assured that the insulator is perfect for all practical purposes. By opening and closing the contact at f alternately, the tester has it in his power to allow currents to pass through his tongue for short intervals, and consequently he will be able to detect the feeblest induction currents by virtue of his changes of sensation.

§ 3. *Detecting Bad Joints.*

From the foregoing it will readily be understood that the instrument may also with advantage be used for detecting bad joints in a telegraph line. It is then only necessary to connect the two ends of the joint by well-insulated wires to the two terminals A and B by means of the binding screws s s; and to plug up hole C, and have the insulator pencil p in the air, *i.e.*, perfectly insulated. In this way the fingers of the tester, on the knobs m and n, and the joint to be tested, act as shunts to the induction coil of the magneto-electric machine. (See dotted line in diagram.)

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[1] Stooping constantly to put the tongue to the knob n is very disagreeable, and therefore a "taster" is supplied with each instrument. An adjustable brass rod is fixed vertically to the screw A, and adjusted to suit the tester's stature. The brass rod terminates in a platinum tip set in an ivory boss. Pressing down the key m with one finger, and applying the tongue to the end of the "taster," has the same effect as placing the tongue directly on the knob n.

§ 4. *Limits of Measurement.*

Any insulator offering a resistance of not more than 1 megohm can be detected by the fingers. Any insulator which has a resistance under 8 megohms can always be detected by the tongue. Any joint which offers a resistance higher than 200 ohms can be detected by the fingers; and from 5 ohms upwards by the tongue.

§ 5. *Rate of Testing; and the economy effected by the use of the Instrument.*

A properly organised testing party, consisting of 10 coolies, 2 line men, and one tester, should always be able to test at least 3 miles of single line per day of 9 working hours. The application of the instrument will be most valuable in all cases, as the lines generally contain only a small percentage of defective insulators, and thus the expense of transport of material to completely re-insulate the lines, which, especially in the case of lines not near a railway, would be very great, is saved.

§ 6. *Practical Remarks.*

1. The best way in practice is to change the insulators for about one mile, to soak them in water for at least twenty-four hours before cleaning, and then test, the tester taking up his position about the middle of the section.

2. Any insulator having a crack in the porcelain is to be replaced by a perfect one, notwithstanding that it may test perfectly. Insulators with cracked porcelains may leak during the wet season, although apparently perfect in dry weather.

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